DETERMINATION OF THE PLASMA PARAMETERS IN GAS DISCHARGES USING THE DOUBLE PROBE METHOD

by

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AUGUST 1984

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A thesis submitted
in Partial Fulfilment of the Requirements
for the degree of

MASTER OF TECHNOLOGY

by

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to the

DEPARTMENT OF NUCLEAR ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

AUGUST 1984

CERTIFICATE

This is to certify that the work "DETERMINATION OF THE PLASMA PARAMETERS IN GAS DISCHARGES USING THE DOUBLE PROBE METHOD", has been carried out by Mr.R.Venu Gopal under our supervision and that it has not been submitted elsewhere for a degree.

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ABSTRACT

Experimental determination of the electron temperature and the number density of electrons has been taken up in the glow discharge plasmas of Argon,Hydrogen, Nitrogen and Air. Double probe method is used to determine the above mentioned plasma parameters. Electron temperatures have been evaluated at different discharge currents. This study includes the pressure range 0.05 torr-0.5 torr and discharge currents varying between 0.5 mA and 20mA.Theoretical evaluation of the electron temperatures using positive column theory is done and the experimental results are agreeable with theoretical results.

Second part of the experimental study includes the diagnostics of the discharge plasmas in magnetic fields. Double probes have been used tranverse to the magnetic field in the whole study. Magnetic field is applied parallel, anti-parallel and transverse to the electric field separately and the electron temperature and n_- have been evaluated using Johnson and Malter's method. As expected from the

theory n_- decreased for increasing magnetic field in parallel and anti-parallel case. However, the trend observed for the transverse case was not as expected. Magnetic field is varied between 100 G and 1000 G. The electron temperatures and the number densities of the electrons are in the ranges 10^4 to 8×10^4 K and $10^8 - 10^{10}$ cm^{-3} respectively.

TO MY BELOVED NANNA, AMMA, BAZI, SYAM,

AND PAPAI

ACKNOWLEDGEMENTS

It is a pleasure to thank Dr.M.S.Kalra and Prof.A.R.Das for their guidance during the course of the present study. I should also thank Mr.S.Balaraman who has helped me in design, fabrication and experimentation. I should also thank Mr.S.S.Pathak and Mr.R.S.Tripathi for their helpful cooperation in making this experiment a success.

I am indebted to the other faculty members whose encouragement was invaluable. I should also thank my friends circle in Hall No.4 whose association gave me inspiration and pleasure during my stay here.

I must thank finally Mr.S.Yadav for typing my thesis patiently and neatly.

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NOMENCLATURE

ω_c	-	Cyclotron frequency
ω_p	-	Langmuir plasma frequency
T_e	-	Electron temperature
T_i	-	Ion temperature
T_g	-	Gas temperature
N_1, N_2	-	Electron densities in vicinity of the probes
V_i	-	Ionization potential
p	-	Pressure of the gas
E	-	Electric field strength
R_e	-	Equivalent radius of the discharge tube
D	-	Diffusion length
L	-	Length of the discharge tube
ϕ	-	$\frac{11600}{T_e}$
R_o	-	Equivalent resistance
V_d	-	Differential probe voltage
i_d	-	Probe circuit current
i_{1+}	-	Ion saturation current to probe no.1
i_{2+}	-	Ion saturation current to probe no.2
i_{1-}	-	Electron current to probe no. 2
R	-	Radius of the discharge tube

i_{2-}	-	Electron current to probe no.2
n_+	-	Ion number density
n_-	-	Electron number density
V_f	-	Floating potential
M	-	Ion mass
I_+	-	Total ion current to the double probe
j_{o1}, j_{o2}	-	Random current densities
ρ, ρ_+, ρ_-	-	Charge densities
D_a	-	Ambipolar diffusion coefficient
λ_e	-	Mean free path of electrons
μ_+	-	Mobility of the ions
j_+	-	Random ion current density
A_s	-	Area of the sheath
A_p	-	Area of the probe
C_{av}	-	Average drift velocity of the ions

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CHAPTER I

INTRODUCTION

In this chapter, we will present briefly the importance and history of gas discharge studies together with a short review of plasma diagnostic techniques. Being one of the first works on probe diagnostics of gas discharge plasmas in our department/institute, most of the background information, both theoretical and experimental had to be obtained during the course of this work. Hence the justification for somewhat extensive review in the present chapter, followed by a detailed literature survey, in the next chapter, on the double-probe method employed in our experimental study.

1.1 Importance of gas discharge studies

One of the oldest disciplines in science is the field of electrical discharges in gases. Sir William Crookes, in 1879, considering the special properties of the matter in discharge tubes, tentatively advanced the idea that such gases should be considered a fourth state of matter. Langmuir, in this connection, in the early 1930's, began using the special designation of "Plasma". Descriptively, the term denotes ionized gases. Depending on the degree of ionization, such gases exhibit similarities to metals, semiconductors, strong electrolytes, and ordinary gases. The concept, " fourth state of matter", thus derives from the extraordinary **array** of physical and chemical properties characteristic of a plasma. Specifically, one recognises the appropriateness of the classification only in those cases where the densities of charges of each sign are approximately equal. This condition is referred to as quasi-neutrality. Some of the examples of the plasma state are electric

discharges in high vacuum tubes, high temperature chemical reactions, atmospheric lightning discharges, earth's upper atmosphere, viz., aurora borealis and aurora australis.

Recently the number of workers in the field has increased faster than ever before. The reason may be the widespread hope of physicists, that by improved knowledge of the physics of ionized gases, the taming of the process of nuclear fusion might be achieved. It is widely recognized that controlled fusion could be the most important means of energy production in the future. In addition to this fascinating target, however, many other ionization phenomena, most of them already utilised in practice, seem capable of further improvements.

1.2 History of gas discharges:

The term gas discharge is used to describe the flow of electric current through a gaseous medium. The requirements for such a passage of current are that some

of the gas particles should be ionized , by whatever means available, and that there should exist an electric field to drive the charged particles so produced to form a current.

The first observations of gas discharges were made in the ccurse of electrostatic investigations. Experimenters from the seventeenth century onwards found that charged conductors gradually lost their charge and that the rate of loss varied markedly with the ambient conditions. By the end of the eighteenth century it had been established that the loss of charge took place not through supports or other solid insulation, but through the surrounding atmosphere. In addition to this leakage, electric sparks were known to many investigaters, and in mid eighteenth century, Benjamin Franklin was experimenting with lightning.

By the beginning of ninteenth century, the advent of continuous current sources had led to the discovery of the electric arc by touching together electrodes

connected to a battery. Between the years 1831 and 1835, Michael Faraday took up research on gas discharges at low gas pressure. He discovered what he called a glow discharge which consisted of a series of alternate luminous and dark zones. In addition, Faraday seems to have been the first to find that the current can pass through a discharge tube filled with a gas at low pressure without showing any luminosity at all. This he called a dark discharge.

In 1858 Plücker discovered that a glow discharge working at a pressure of the order of 10^{-2} torr emits cathode rays. The beam which originates from the cathode colours the gas along its path, and when it impinges on the glass wall of the discharge tube , a green fluorescent spot is produced. Hittorf observed in 1869 that these cathode rays are deflected in a magnetic field, and Goldstein in 1876 and Hertz in 1883 showed that Cathode rays are deflected by an electric field.

It was first thought that the transport of electricity through gases took place in a similar way to the transport of charges through conducting liquids. However, Crookes, who at that time investigated discharges at low pressures, visualised charge carriers quite different from those assumed to exist in electrolytes. Sheffield in 1874 put forward the first hypothesis that cathode rays are most likely to be the fundamental particles of the atom.

There followed a period rich in discoveries. H.Hertz observed in 1887 that light emitted by a spark caused a nearby spark gap to breakdown more easily. One year later Hallwachs discovered that a zinc plate which is irradiated with ultraviolet light becomes positively charged. Soon it became clear that the cathode rays must have a mass much smaller than that of the lightest gas atoms. Thus they were taken as being atoms of negative electricity and Stoney in 1891 proposed for these particles

the name 'electron'. J.J. Thomson, Kaufmann and Wiechert derived from the fact that the charge to mass ratio of the cathode rays is independent of pressure, nature of the gas , and material of the cathode, that the particles are of a type common to all elements and thus distinct from electrolytic ions.

The existence of rays of positive ions was first shown by Goldstein in 1886, who passed these 'canal rays' in to an adjoining chamber through a hole in the cathode of a glow discharge. Later investigations by J.J.Thomson, F.W Aston and W.Wien furnished valuable information about the properties of beams of positive ions.

In twentieth century the pace of research accelarated. Engineers became interested in discharge tubes and plasmas, and introduced them into everyday life in the form of domestic fluorescent lighting and neon signs. In addition, long wave radio communication depends on varying proporties of the ionosphere (a natural plasma)

as well as on radio engineering techniques, thus again illustrating the influence of plasmas on every day life.

Today success in producing controlled nuclear reactions has widened yet further the horizons and ambitions of scientists and engineers. Nuclear reactors which depend on the fission of solid uranium have brought about a revolutionary progress in our conception of energy sources, and they have had so great an impact both with general public and with research workers and politicians that an investigation of "fusion" reactors is now contemplated. These studies involve the use of an extremely large discharge tube and employ an inexhaustible source of fuel, since this fuel is hydrogen or one of its isotopes. Several nations have already visualized and initiated several " fusion" projects on a commercial basis, thus providing numerous opportunitiesfor scientists to work in this field.

1.3 Importance of gas discharge studies in magnetic fields:

Although gas discharge studies in magnetic fields had their origin when scientists tried to investigate the properties of cathode rays, the current interest in these studies is derived from their relevance to thermonuclear fusion. It is clear that one of the major problems of commercial power production by nuclear fusion is that of containment. By some means we have to prevent the plasma from heating the walls of the vessel containing it, which would both vaporize the walls and also by loss of heat prevent the temperature from rising to the very high level needed. The only method that has been seriously suggested for preventing a devastating loss of heat by particles hitting the walls of the vessel is use of strong magnetic fields. Hence it is of great value to study the plasma behaviour under magnetic fields and there are various methods of applying magnetic fields depending upon the geometry of the system. Recent studies involve toroidal devices, stellarators, pinch devices, and magnetic mirrors.

1.4 Plasma diagnostic techniques:

Plasma diagnostics deals with the determination of various physical properties of plasmas. In one sense plasma diagnostics is coexistent with the whole of plasma research. Every plasma experiment must incorporate different means of sampling and monitoring plasma properties, and all the effects which are observed have some diagnostic significance. Plasma diagnostics has a somewhat inter-disciplinary character, borrowing its methods from many branches of physics including optics, spectroscopy, high-energy physics, microwave technology, and fluid mechanics.

Plasma diagnostics may be said to have originated in the work of the astrophysicists, and many of the underlying principles of the plasma state, as well as most of the spectroscopic techniques in present use, have been adapted from methods first developed by them. But the pioneering study of electrical discharges by Crookes,

Townsend and Thomson really represent the first important chapter in laboratory plasma research.

Perhaps the figure that stands out most prominently among the pioneer workers in plasma research is that of Irving Langmuir. He first used the term plasma as descriptive of the oscillations that were observed in a low-pressure mercury discharge, there by naming the new field.

The physical properties of plasmas are subdivided into two categories. They are microscopic and macroscopic properties. An example of microscopic properties is collision frequency. The macroscopic properties are either static (such as density, pressure and temperature); or transport (such as viscosity, diffusivity, heat conductivity, and electrical conductivity). In addition, there are many other variables, for example, electrical (current, voltage and power) and dynamic (mass flow, velocity, thrust, and others)

Two basic types of diagnostic methods are those measuring global quantities and those measuring local ones. The local quantities are measured as functions of both space and time.

Methods of measurements lie between two extremes, namely, those interfering with the flow and those not interfering with it. The former group employs solid probes; the latter uses microwaves, optical spectroscopy, particle beams, and lasers.

Probes constitute the most common method used to obtain detailed information of the internal structure of plasmas. Probe methods have limited applicability, since they usually disturb the very quantities intended to be measured. The various types of probes represent different degrees of disturbances to the flow and also possess different ranges of operation. Sometimes the introduction of probes into a plasma is not permissible because the probe may be damaged by sputtering. Impurities introduced

by the evaporation of probe material contaminate and cool the flow. In the special case of Langmuir probes, the current and voltage characteristics of the probe are altered by secondary and thermionic emission. Probes are categorised into two types, such as electric probes and magnetic probes. Electric probes may be used to measure electron temperature, electron and ion densities, space and wall potentials, and random electron currents. There are various types of electric probes, namely, single electric probe, guarded ring probes, double electric probes, etc. Magnetic probes may be used to measure magnetic field distributions, current densities, pressures, and electric conductivities.

Spectroscopic methods may be applied in the optical, ultraviolet, and X-ray regions of the spectrum. These methods are based on emission spectra. They employ photographic and photo electric record equipment.

Microwave methods use radiation which may be considered as close to equilibrium radiation . This situation appears in the vicinity of cyclotron frequency ω_c and the Langmuir plasma frequency ω_p and usually lies in the millimeter microwave region. These methods utilize instruments called microwave interferometers.

Thomson scattering of laser light may serve as a new diagnostic method. In concept, the idea is similar to radar. Another method for fast density measurements is probing with energetic particle beams.

1.5 Outline of the present work:

In our experimental study we tried to investigate electrical discharges of argon, nitrogen,hydrogen and air. We mainly confined our study to glow discharge region. We tried to investigate the behaviour of these discharge plasmas with and without magnetic fields present. Electric double probes have been used to study these plasmas. We fabricated two discharge tubes, one for the studies

under magnetic fields and the other for the studies without magnetic fields. We studied the behaviour of the plasma when the magnetic fields are longitudinal as well as transverseto the length of the discharge tube.

In Chapter II, we discuss in detail the literature available on the double probe technique. Chapter III deals with the qualitative treatment of glow discharges and the theory of the double probe method. In Chapter IV, we present details of our experimental setup and the observations made by us. In Chapter V, we ddiscuss the results, draw conclusions, and give suggestions for further work.

CHAPTER II

REVIEW OF LITERATURE ON THE DOUBLE PROBE METHOD

2.1 Single probe vs the double probe:

In gas discharges either of stationery or time-varying type it is generally the case that the electrons present in the plasma regions have a Maxwellian distribution. If this is so the concept of temperature can be associated with the electrons. The electron temperature is denoted by T_e .

Langmuir and Mottsmith [1] have described a single probe technique for measuring electron temperatures as well as of other quantities such as electron density and wall and space potentials. Their method can be used for stationary discharges and for certain types of time-varying discharges. Unless its area is extremely small, the probe may draw sufficient electron current when operated close to space potential to disturb the discharge conditions which it is designed to measure.

A double probe method (DPM) has been suggested and developed which exerts a negligible influence on a discharge and which seems to yield accurate temperature data in all types of discharges including a decaying plasma.

2.2 Early work on the double probe method:

Reifmann and Dow [2,3] have described a double probe method for measurements in the ionosphere. It consists of using an isolated two-electrode system as an "ionosphere probe" on a high altitude rocket. By applying a periodic sawtooth voltage to the electrodes and recording the the resulting current, a series of volt- ampere characteristics are obtained. The logarithm of electron current measured as a function of the differential voltage between the two electrodes is calculated from these characteristic curves and plotted . These plots are very nearly linear. Ion densities in the E-layer calculated are of the order of 10^5 cm^{-3} and the electron temperatures range from 2500K- 5000K.

Kojima and Takayama [4] have also used the double probe method for high frequency electrodeless discharge. They have used a pair of probes in an hf field (about 200 M Hz) applied between the parallel electrodes, in which discharge tubes are put. Discharge tube contains argon gas at the pressure 1-10 torr. They noticed that when the probes are not arranged in neutral position, the probe current has no symmetrical nature and often some current flows at zero voltage. They have also found that the saturation current depend only on the area of the probe which has negative veltage. They have suggested a method by which we can measure electron temperature, T_e, from the probe characteristics. In calculations they made use of the value of the voltage at which probe current is zero (V_o). They derived a formula:

$$V_o = - \frac{kT_e}{e} \ln \left[\frac{N_2}{N_1}\right] \qquad (2.1)$$

Where k is Boltzmann constant, e is the charge of the electron, N_1 and N_2 are the electron densities at each probe

respectively. They assumed the density of electrons is same as that of positive ions, and used N_2/N_1 as the ratio of saturation currents. Electron temperatures vary from 2.5×10^4 K to 2.8×10^4 K.

Quite extensive study of the double probe method in gas discharges has been done by Johnson and Malter [5]. They employed double probes to study decaying plasmas. They gave a qualitative treatment of the functioning of a double probe and suggested methods to evaluate the electron temperatures from the characteristic curves. The suggested methods are logarithmic plot method, equivalent resistance method, and the intercept method. They also showed that each of these methods give nearly the same results by giving illustrations of probe plots obtained from different discharge tubes. They have also calculated floating potential, electron and ion densities, and wall potential from the calculated electron temperature. They worked with cylindrical triode and a diode filled with

argon at pressures 1 torr and 250 microns respectively. Electron temperatures obtained were of the order of 10^3 K and number densities are of the order of $10^9 cm^{-3}$.

Kojima and Takayama [6] have compared the methods of calculating electron temperatures suggested by them earlier (4 with that of Johnson and Malter [5]. They experimented with argon at 7 torr in a high frequency discharge. Temperatures calculated from both methods are in excellent agreement. They also found that in hf discharges electron temperature at any point in a plasma is same and that the electron temperature rise is rather small compared with the increase in the density of the plasma.

K.S.Knol[7] studied the determination of the electron temperature in gas discharges by noise measurements. The use of an electric discharge in a gas as a microwave noise source has been studied. The electron temperatures of He, Ne, Ar and Xe are measured as a function of the gas pressure and the direct current. A comparison of

these measurements is made with a theoretical formula for the electron temperature as a function of the product of the gas pressure and the radius of the discharge tube. The theoretical formula which they used is

$$\left[\frac{eV_i}{kT_e} \right]^{-\frac{1}{2}} \exp\left[\frac{eV_i}{kT_e} \right] = 1.16 \times 10^7 \quad c^2 p^2 R^2 \qquad (2.2)$$

where V_i is the ionization potential, p the pressure in torr, R the radius of the discharge tube in centimeters and c is a constant depending upon the properties of the gas [7]. They have found that there is a slight decrease in T_e with increasing discharge current in the pressure regions 0.5 - 10 torr. In addition to noise measurements to determine the electron temperature, they have also employed single probe method. The agreement between the two methods of measuring is satisfactory.

A modified floating double probe method has been presented by Kojima , Takayama and Shimauchi [8] .

The double probe consists of a rod probe and a forked probe. Argon discharges in the region between 0.26 and 1 torr at 170 MHz have been studied. By adjusting the probes in the direction of hf field , they have found that the characteristic is shifted to some voltage V_a. By analysing the curve the determination of field strength was tried. They derived an equation

$$I_o\left[\frac{e\sqrt{2}\ El}{kT_e}\right] = \exp\left[\frac{eV_a}{kT_e}\right] \qquad (2.3)$$

where V_a is the voltage at which the characteristic curve is crossing the coordinate axis, E is the r.m.s field strength, 2l is the distance between probes, T_e is the electron temperature, and I_o is the Bessel function of zeroth order of imaginary argument. Using (2.3) they determined field strength E by measuring V_a. For theoretical evaluation of the electron temperature of the hf plasma they made use of the Eq.(2.2). To account for the diffusions in the direction of the axis of the

tube, they suggested to use equivalent radius of the tube, R_e, which was defined by

$$R_e = 2.405\ D \tag{2.4}$$

where D is the diffusion length [9] given by

$$\left(\frac{1}{D}\right)^2 = \left(\frac{\pi}{L}\right)^2 + \left(\frac{2.405}{R}\right)^2 \tag{2.5}$$

L and R being the length and radius of the cylindrical tube. The experimental values of the electron temperature and field strengths are in good agreement with theoretical results.

2.3 Applicability of the double probe and recent work:

Yamamoto and Okuda [10] gave a criterion for the applicability of the double probe method. In their paper they discuss the correct application of the double probe theory and discuss some problems in connection with this method. They derived a general expression for T_e, when the saturated part has a considerable slope.

The criterion for the applicability of the usual double probe method as given by them is

$$A \gg 0.693 \left(\frac{S}{\phi}\right) \qquad (2.6)$$

where S is the slope at large differential voltage between probes (V_d), A is half of the sum of the ion currents at $V_d = 0$, and $\phi = \frac{11600}{T_e}$. When saturation regions are having considerable slope, they made a correction to equivalent resistance method through which electron temperature can be exactly calculated. Their expression for T_e is

$$T_e = 5800\ A \left(\frac{1}{R_o} - \frac{S}{2}\right)^{-1} K \qquad (2.7)$$

where R_o is the equivalent resistance as defined by Johnson and Malter [5]. Johnson and Malter case is a special case where S=0. They also suggested a floating triple probe method to measure electron energy distribution in electrodeless and hf discharges. The floating potential is discussed in detail and expression is given showing

good agreement with measured values.

For probes of equal area, the electron temperature can be obtained directly from the probe plots by the equivalent resistance method. With probes of unequal area, however, the electron temperature is obtained from the slope of the semi-log plot of probe current against biasing voltage. For this purpose, Jones and Saunders [11] have designed a circuit to display the semi-log plot directly on an oscilloscope. The apparatus provides a pulse of biasing voltage to a probe system so that electron temperatures up to 2×10^5 K and ion densities up to 5×10^4 cm^{-3} can be measured. The system consists of a low impedance voltage sweep generator, a transformer-coupled measuring circuit and a logarithmic amplifier.

F.F.Chen [12] have used double probe method for studying unstable plasmas in the presence of strong magnetic fields. The plasma was produced by hot-cathode

discharge in a magnetic field of 4000 G and has a density of the order of 10^{12} cm^{-3}. With the help of the electronic circuit the voltage between probes was swept and the characteristic was displayed on the oscilloscope screen. Measurements were also done with a dc probe taken with an X-Y recorder. Radial variation of the electron temperature has been studied. Temperatures are varying between 3 and 4 electron volts.

V.K.Rohatgi [13] measured the electron temperature in a confined electric arc at 1 atm of argon using double floating probe technique. Probe characteristics are taken at different arc currents. The probe current increased with both increasing main-arc current and increasing bias voltage. They estimated electron temperatures from the expression given by Cozens and Von Engel [14], such as

$$T_e = \frac{e}{2k} \, i_p \left(\frac{dV_d}{di_d}\right)_{V_d=0} \qquad (2.8)$$

where i_p is the ion current to a probe, V_d is the voltage between the probes and i_d is the probe current. The temperatures ranged from 12000 K to 15000 K. As the arc current increased temperature was also found to be increasing. They compared probe data with spectroscopic measurements and they are found to be in good agreement. They evaluated the electron density using Saha Eq.[15] as well as from continuum probe theory[16] . The results obtained are compatible with each other.

In his theoretical formulation, J.D.Swift [17] investigates the conditions which must be satisfied in order that the energy distribution function of electrons in a collisionless plasma may be obtained by the Druvesteyn method using an asymmetrical double probe system. If the error in the determination is to be less than 3% he has shown, in the case of nitrogen ions, that N_2A_2/N_1A_1 must exceed 6×10^3, where A_1, A_2 are the areas of the probes and N_1, N_2 are the

electron densities in the vicinity of the two probes.

R.M. clements and . . . H.M. Skarsgard [18] measured electron temperatures and densities in a weakly ionized helium after glow with cylindrical double probes and compared with the measurements obtained using a microwave radiometer and a microwave resonant cavity. In the absence of a magnetic field the gas pressure was varied to give conditions ranging from collisionless to collision-dominated (i.e 0.1 to 8.5 torr) and, at low pressure, different magnetic field strengths were employed up to values such that the electron Larmor radii were much smaller than the probe radius, although the ion Larmor radii were larger. The plasma source consists of an oxide cathode discharge tube of length 130 cm and bore of 25 mm. A steady axial magnetic field, variable up to 0.11 Tesla is produced by eight coils mounted coaxially with the discharge tube. Discharge current ranges from 10mA to 1A.

All measurements are made in the after glow of the positive column.

The electron temperature T_e is determined by using the equivalent resistance method. The expression for T_e they used is same as the Eq. (2.8) . The density is deduced from the probe characteristic using an analysis of the saturation ion current to a probe at the floating potential in a collisionless plasma as suggested by Lam[19] They concluded that the assumption of a Maxwell-Boltzmann distribution for the electrons, at a temperature unaffected by the presence of the probe, is valid for the range of conditions studied.

Blue and Stanko[20] did experiments to compare single - probe measurements with double probe measurements. Probe measurements were made in a repetitively pulsed rf discharge plasma of helium at 1 torr. Their studies were done in an after glow plasma and they observed that at late times in an after glow the electron energy distribution is Maxwellian with a temperature corresponding to the ambient temperature.

Hasebe[21] measured electron temperature in the positive column of a mercury-argon discharge operated at a constant discharge current of 0.23 A, from 150 to 6000 Hz ac supplies. He made use of double probe technique. He has shown that the luminous efficiency increases at higher supply frequencies.

Lacoste and Dimoff [22] demonstrated an electronic circuit to sweep the voltage of a double probe adaptable to measure plasma characteristics generated by a high voltage discharge of argon at 2 torr pressure. They displayed the complete characteristic on an oscilloscope screen and temperatures were evaluated from the obtained characteristics.

Kawashima and Yamori[23] have given a method to directly display the density and electron temperature by detecting the phase reversal of the third harmonic component of the ac signal applied on floating double probe. The phase reversal of the third harmonic component

was observed at a voltage equal to 1.30 kT_e and from detecting this voltage and the corresponding probe current, n_e and T_e were obtained.

J.J.Lee [24] used double probes to measure the parameters of a He plasma beam produced by a conical Marshall gun. The temperatures they obtained were of the order of 20 eV and the electron densities of the order 10^{16} cm^{-3}. The results obtained were in general agreement with those obtained by laser interferometric and spectroscopic techniques.

Schneider and Szubert [25] also proposed an electronic circuit used with floating Langmuir double probes in plused plasma measurements. Argon at a pressure of 8 microns was used in the experiment and a sine wave with an amplitude of 1000 A was applied to plasma tube. Current fluctuations of the double probe are transformed by means of a special transformer in to voltage fluctuations. Their experiment shows that the electron

temperature increases with a small difference as the main discharge current is increased. Discharge current varied between 350 A and 1000A. Electron temperatures are in the range of 30740 K - 33740 K.

So far we have listed most of the literature available on the double probe diagnostics. Studies on this subject also have been done by Makita etal, [26], Hoegner [27], S. Togo [28], Cozens [29], Friedman [30], and several others. Theory of electric probes, their construction, and various experimental considerations are discussed by F.F.Chen [31] and Lochte and Holtgreven [32].

2.4 Comments on the literature:

We have reviewed most of the available literature on the double probe diagnostic techniques and it is certain that it is one of the best techniques, easily implemented and very simple to analyse the local conditions of the plasma. But very few studies are done on the double probes in magnetic fields. Keeping this point in view we took up the study of the double probe

diagnostics in the presence of magnetic fields (transverse as well as longitudinal to the discharge tube) in various gas discharge plasmas. We hope our present study reinforces the developments on this subject and provides a good understanding of the gas discharges under magnetic fields.

CHAPTER III

THEORY OF THE GLOW DISCHARGE AND THE DOUBLE PROBE METHOD

3.1 Types of gas discharges

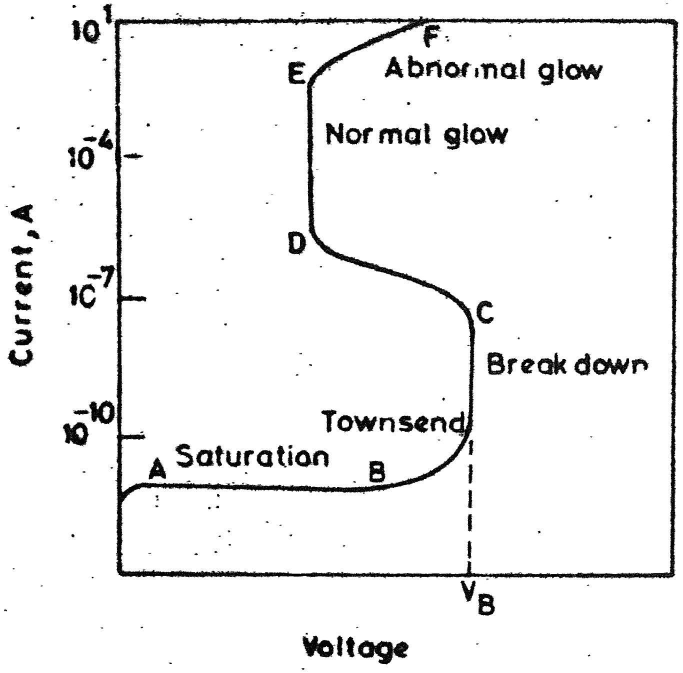
Gas discharges in the steady state may conveniently be classified into three types according to the current which they carry. These are:

(i) The Townsend discharge, which carries currents up to 10^{-6}A. (Fig. 1)

(ii) The glow discharge, which carries currents from 10^{-6} to 10^{-1} A approximately. (Fig. 1)

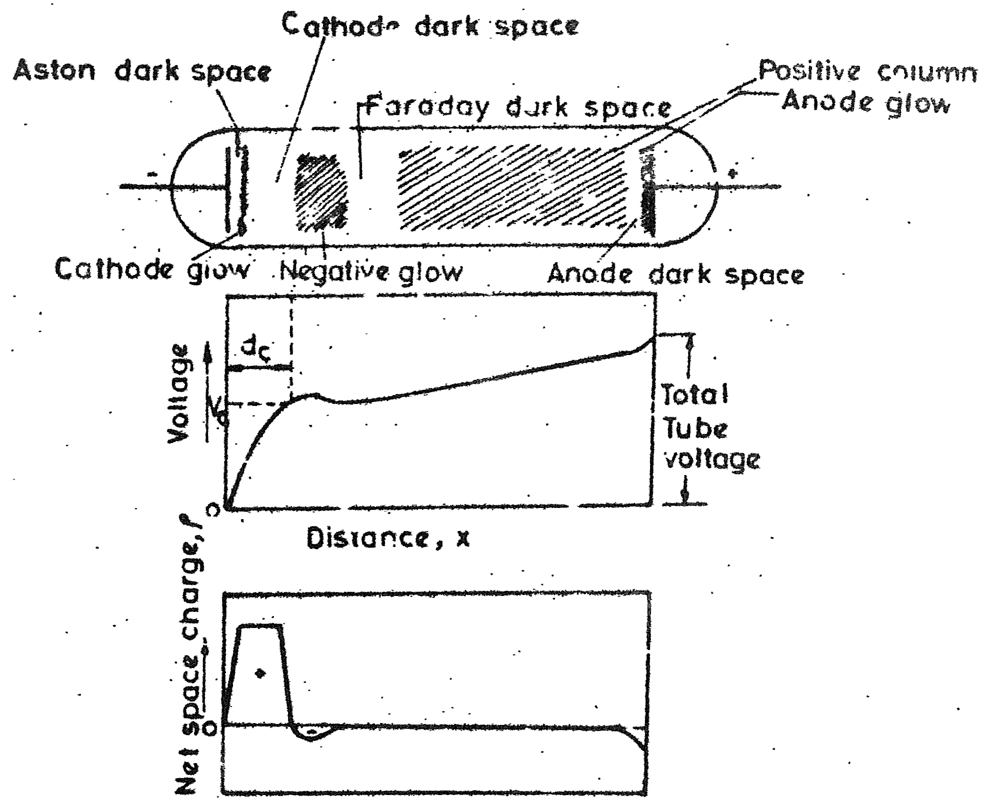
(iii) The arc discharge, which carries currents of about 10^{-1} A upwards.

The Townsend discharge is characterised by its very small currents; it is invisible because the density of excited atoms which emit visible light is correspondingly small. It is not a self-sustaining discharge in that it does not entirely provide its own ionization but requires external agencies to produce electrons. The Townsend discharge is most easily observed by applying a potential of the order of



Schematic characteristic for a gaseous discharge

FIG.1



Glow discharge at low pressure

FIG. 2

100V between two electrodes in a gas at a pressure of few torr and using a sensitive device to measure the current flowing.

If the voltage across a discharge tube carrying a Townsend discharge is increased, the current will at some stage increase sharply by several orders of magnitude. This is the breakdown point, and this occurs at voltages ranging from two to three hundred volts upwards, depending on the pressure and the nature of the gas and the separation of the electrodes.

Once breakdown has occured, the discharge becomes self-sustaining and takes the form of a glow or an arc discharge, depending on the gas and circuit conditions.

If the pressure is not more than a few torr , it is most likely that a glow discharge will form upon breakdown; the gas then emits a diffuse glow of characteristic colour with several distinct regions and passes a current which is probably a few milliamps with a potential difference not greatly different from that at which breakdown took place.

We will discuss in detail about the glow discharges in the subsequent sections.

If on the other hand, the pressure of the gas is nearer to atmospheric , and if the resistance of the external circuit is comparatively low, then breakdown is likely to result in an arc discharge. Here the gas is intensely luminous and may give the impression of violent turbulence. The current is determined mainly by the external circuit, and the voltage across the discharge is low, usually some tens of volts.

3.2 The dc low-pressure glow discharge:

The typical current-voltage characteristic of a gaseous discharge is shown in Fig.1. The dc glow at low pressure is one of the most familiar of gas discharges, largely because of the ease with which it can be produced and maintained, and because of its distinctive appearence which, depending on the pressure used, can be shown in Fig. 2. The length of the discharge is composed of several regions to which are given the names indicated, and the

voltage along the discharge is found experimentally to vary as shown. From the voltage distribution, the space charge ρ can be obtained by Poisson's Equation.

If the discharge is operating within the region DE of Fig. 1, it is found that the cathode glow covers only a part of the cathode surface, and that this part increases or decreases in area apparently in proportion to the current flowing. Further, at the point E where the voltage across the tube begins to rise with current, the whole surface is covered by the cathode glow. The current density at the cathode remains constant and the tube voltage also remains constant. But if the current density is allowed to increase, the voltage also rises. Cathode glow some times establishes on additional surfaces such as on the metal supports behind the electrodes. The region DE is said to refer to normal glow, while a discharge in the region EF is called an abnormal glow.

(a) Cathode region

This is the name given to the region of length .

d_c(Fig.2) stretching from the surface of the cathode to just upto the region of commencement of the negative glow. It corresponds to the cathode fall in potential V_c. The theory relating to phenomena with the cathode region is based on the following hypotheses:

(i) All the cathode electrons are emitted under the effect of ion bombardment.

(ii) The electric field in the vicinity of the cathode decreases linearly as function of distance, x

(iii) All theions which appear in the cathode region make it behave as a Townsend discharge tube.

In the Aston's dark space (Fig.2), the electrons coming from the cathode do not have enough energy to ionize or to excite the atoms of the gas. This region does not emit any visible radiation .

The cathode sheath will appear at the point where ions excited by electrons return to their ground level.

In the cathode dark space the gas is ionized by the electrons which have not lost any energy in exciting

the atoms of the cathode sheath, but which , on the other hand, have been accelarated by the electric field. Multiplication of charges results, but the electrons liberated do not have enough energy to excite the gas. Due to this lack of excitation or recombination, this region emits little light.

(b) The negative glow

In this region, the large number of secondary electrons liberated in the dark space begin to excite the ambient gas atoms. There is therefore an abundant emission of light. But the electric field decreases and with it the energy of the electrons and the intensity of the light emitted. Since the density of ions is great in this region, there are a large number of recombinations. Nevertheless, the recombination radiation is not very intense.

(C) Faraday dark space

In this region, the electrons which lost their energy in the region of negative glow can not excite or ionize the atoms of the gas. The field here is so small that they can not regain much energy . The electric current in

this zone, as in the positive column, is essentially a current due to the diffusion of the charged particles.

(d) Positive column

The positive column fills most of the discharge tube from the Faraday dark space to the anode. It is not the characteristic of the luminous discharge if the distance between the electrodes is too small. The positive column is an example of a plasma and its effect is beyond the scope of classical discharges.

The positive column is the most luminous part of the tube after the negative glow. It may be homogenous or striated. These striations appear under certain conditions of pressure, geometry and current and in certain gases. They may be fixed or move with a longitudinal velocity in the direction of the cathode. The electrons are not very fast in this region since E is very small and practically constant.

$$\frac{dE}{dx} = \frac{d^2V}{dx^2} = 0 \qquad (3.1)$$

But this means that (according to Poisson's equation)

$\rho = \rho_+ - \rho_- = 0$ where ρ, ρ_+ and ρ_- are the charge densities or $n_+ = n_-$ where n_+ and n_- are the number densities of ions and electrons respectively. This is the definition of a plasma. The value of n_- or n_+ is of the order of $10^{10} cm^{-3}$ at a pressure of 1 torr. The temperature of the gas and that of the positive ions remain close to the ambient temperature while that of the electrons is several tens of thousands of degrees.

3.3 Theory of homogenous positive column at low pressures

In the steady uniform column the electric field must have such a value that the number of electrons and ions produced per second just balances the loss of charge. This theory is based on the following premises:

(a) At every point, the macroscopic charge density is zero: $n_- = n_+ = n$

(b) Charged particles are lost to the lateral walls and are neutralised by recombination.

(c) Recombination in volume is negligible (T_e high and n small)

(d) Ionisation is simple and not cumulative.

(e) There are no negative ions other than the electrons.

(f) The end effects are negligible except for the entry and the exit of macroscopic electron and ion currents.

(g) The radius of the column is large in comparison with the m.f.p (mean free path) of the electrons.

(h) The density n of ions and electrons becomes zero at the walls.

(i) The lateral walls are assumed to be made of insulating material (glass, for example).

These premises show the importance of the walls in the case of the positive column while they play no part at all in the cathode region of the discharge.

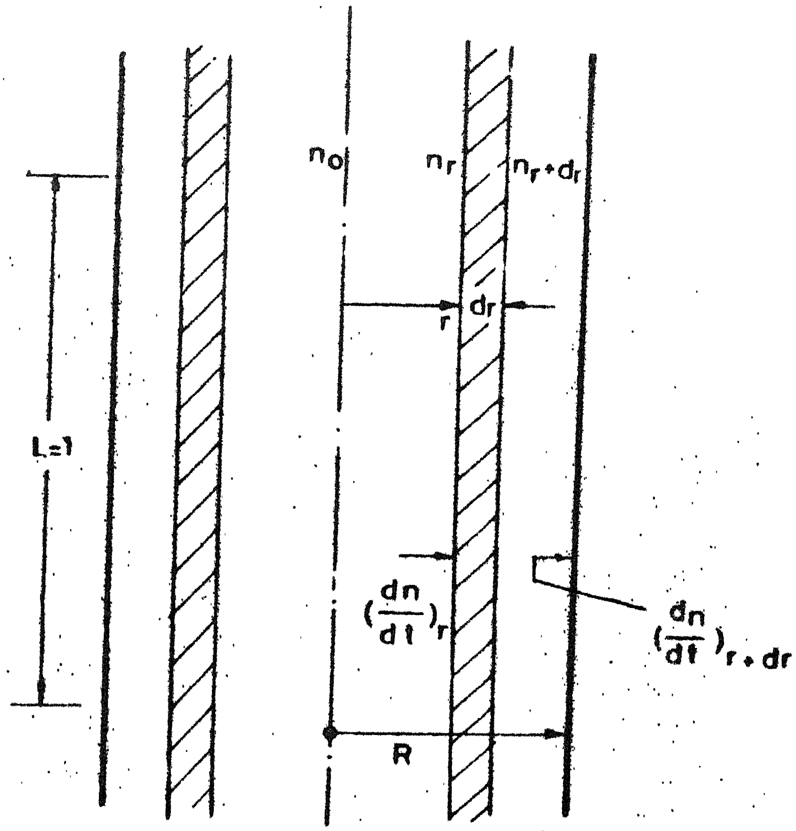
3.3.1 The radial distribution of charges:

Let the mean free path of electrons $\lambda_e \ll R$ (See Fig.3), so that diffusion laws apply. We have

$$n_+ \approx n_- = n \qquad (3.3)$$

and

$$\frac{dn_+}{dr} \approx \frac{dn_-}{dr} \doteq \frac{dn}{dr} \qquad (3.4)$$



To derive the radial distribution of charges in a long cylindrical positive column

FIG. 3

From Fig. 3 the number of ion pairs entering the volume element dr radially per unit length of the cylinder is

$$\left[\frac{dn}{dt}\right]_r = -2\pi\, r\, D_a \left[\frac{dn}{dr}\right]_r \qquad (3.5)$$

The number leaving dr is

$$\left[\frac{dn}{dt}\right]_{r+dr} = -2\pi (r + dr) D_a \left[\frac{dn}{dr}\right]_{r+dr}, \qquad (3.6)$$

where D_a is the coefficient of ambipolar diffusion and n the concentration of ions and electrons. Since for reasons of symmetry and absence of recombination in the gas $\frac{dn}{dt} = 0$ at $r = 0$. Thus from Eqs. (3.5) and (3.6) the number leaving dr by diffusion exceeds the number entering it by

$$dZ_{diff} = 2\pi\, r\, D_a \left[\frac{1}{r} \frac{dn}{dr} + \frac{d^2n}{dr^2}\right] dr. \qquad (3.7)$$

This number loss has to be balanced by ionization in the same element dr. Let each electron make q ionizing collisions per sec; thus we have

$$dz_{ioniz} = 2\pi r q\, n\, dr\ , \qquad (3.8)$$

where q is rate of ionization.

Equating (3.7) and (3.8), we find the differential equation

$$\frac{d^2n}{dr^2} + \frac{1}{r}\frac{dn}{dr} + \frac{q}{D_a} n = 0. \qquad (3.9)$$

The solution is a Bessel function of zeroth order and real argument

$$\frac{n_r}{n_o} = J_o[r\sqrt{(q/D_a)}] = J_o(x). \qquad (3.10)$$

Since concentration is a positive quantity and $n_r = n_o$ at $r=o$, the positive part of the $J_o(x)$ has to be applied

$$\frac{n_R}{n_o} \simeq 0 \qquad \text{at} \quad x = R.$$

Hence from (3.10), $x_R = R\sqrt{(\frac{q}{D_a})} = 2.405,$ (3.11)

the first zero point of J_o, and substituting it in (3.10), we obtain the distribution

$$\frac{n_r}{n_o} = J_o(2.405\, r/R). \qquad (3.12)$$

The concentration of charges in a positive column varies with r in a nearly parabolic manner.

3.3.2 The electron temperature:

Electrons are assumed to have Maxwellian distribution. Both D_a and q depend on T_e . From the relation $R\sqrt{(q/D_a)}=2.405$, it is therefore possible to find T_e as a function of the other parameters of the discharge: radius R, pressure p and the nature of the gas.

$$D_a = \mu_+ \cdot \frac{kT_e}{e} . \qquad (3.13)$$

The value of q is calculated by supposing that the speed distribution is Maxwellian

$$(dn)_{(v,v+dv)} = 4\pi\, n \left(\frac{m}{2\pi\, kT_e}\right)^{3/2} v^2 \exp\left(-\tfrac{1}{2}\, mv^2/kT_e\right)dv. \qquad (3.14)$$

This is justified by measurements and the results which illustrate the fact that the electric field in the positive column is too small to perturb the thermodynamic equilibrium to any extent. Under these conditions, the rate of ionization, q is approximately given by

$$q \approx a_g p V_i^{3/2}\, e^{-x}/\sqrt{x} , \qquad (3.15)$$

where

a_g = constant dependent on the gas used

p = pressure

V_i = ionization potential of the gas

x = $\dfrac{eV_i}{kT_e}$.

Finally substituting $R\,(q/D_a)^{\frac{1}{2}} = 2.405$ in (3.15) we get

$$\frac{e^x}{x^{\frac{1}{2}}} = 1.16 \times 10^7 \; c^2 \; p^2 R^2 \qquad (3.16)$$

(p in torr and R in cm)

where c is a constant and its approximate values for various gases [36] are given in Appendix-A. K.S. Knol [7] and Okuda, Takayama and Shimauchi [8] have also used an equation similar to Eq. (3.16) for evaluating electron temperatures theoretically.

It should be noted that T_e depends only on pR and it is independent of the distance r from the axis. Loss of charge due to diffusion increases as the radius of the tube diminishes. To conserve the same current, the ionization power would have to increase which entails a rise in temperature.

With higher currents, the heating may be such that the pressure p rises sharply at the axis. Theoretical determination of T_e should take this into account. The temperature T_e of the ions rises little above that of the neutral particles and the ambient temperature.

3.4 Positive column in magnetic field:

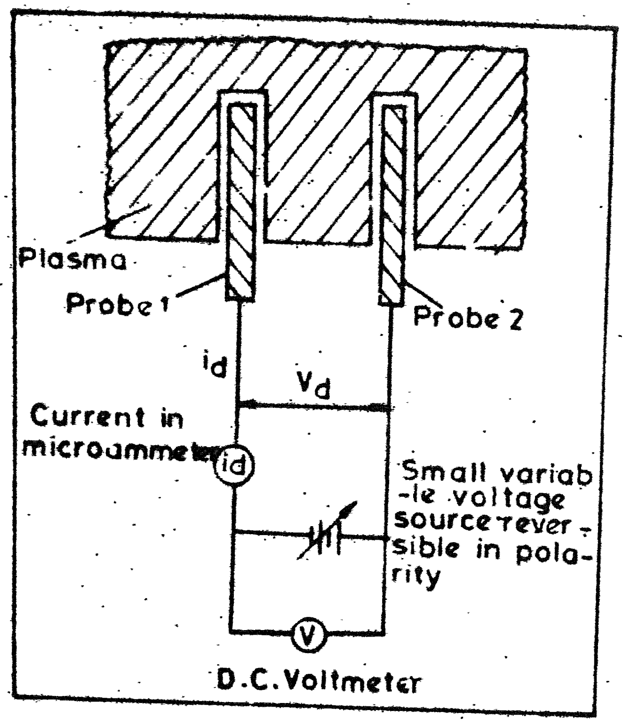
A magnetic field H applied parallel to the axis of the column reduces the radial flow of electrons crossing the boundary of the positive column - the region between column and wall which is controlled by the negative wall charge, and produces an axial flow of electrons. Since the number of electrons arriving at the wall decreases with increasing H, fewer positive ions must reach the wall, equilibrium being assumed. Hence the wall becomes less negative and so T_e and E are reduced [37].

A transverse magnetic field presses the column against the wall which increases the losses there more than it reduces the losses on the opposite side. The result is increase in T_e and E/p [38].

3.5 The Double Probe Method (DPM)

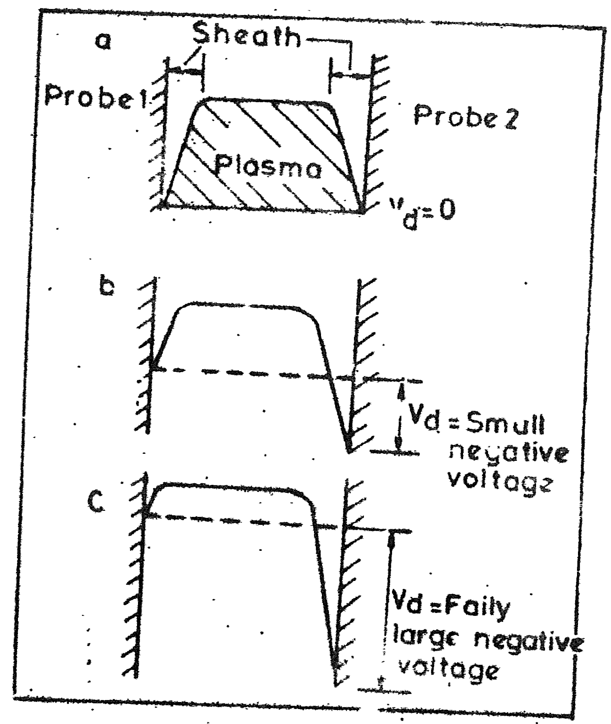
In most gas discharges there is an electrode in good contact with the plasma which can be used as a reference point for potential when applying a bias voltage to a probe. Such an electrode can be the anode or the cathode of a discharge, or the metallic wall or limiter of an electrodeless discharge, such as that in a stellarator or a toroidal pinch. In some instances such a reference point is not available. Examples of this are a toroidal rf discharge in a glass tube or the plasma in the ionosphere. In such a case a double probe must be used. The double probe method was originally proposed by Johnson and Malter [5], and we shall give a simplified version of their thorough analysis. This method was invented for use in decaying plasma, in which the plasma potential changed with time, so that it was difficult to maintain a contact probe-plasma potential difference.

The double probe method (DPM) makes use of two probes, each similar to the single probe of the single probe method (SPM). They are biased with respect to each



Johnson and Malter's double-probe connections

FIG. 4



Schematic representation of the effects of potential differences on the double probe

FIG. 5

other but insulated from ground, the entire system "floats" with the plasma and therefore follows the change of plasma potential . The circuit is shown in Fig. 4. The potential V_d is termed the differential probe voltage, and its associated current, i_d the circuit current. The positive sense of these quantities is established by the arrow directions where we define positive current as the rate of flow of positive charge.

As with the SPM the DPM is based on the Boltzmann relation and the plasma-sheath properties of a gas discharge. In addition it is based on an application of Kirchoff's current law which requires in this case that at any instant the total net current of positive ions and electrons flowing to the system from plasma must be zero.

3.6 Qualitative treatment of the double probe

As an aid in understanding the mathematical formulation, let us consider qualitatively how the system reacts for several values of V_d. For simplicity, let us

first assume that both probes are equal in area and that no contact potentials or differences in plasma potential from point to point exist. Furthermore, we assume that V_d has no effect on the ion current to the system. This is very closely approximated in practice.

(a) V_d = 0 (Fig. 5 a)

Each probe will collect zero net current from the plasma and will ride at the same floating potential. The current i_d must be zero since no net potential acts in the current loop. This condition corresponds to point O on the curve of Fig. 6 .

(b) V_d = Small negative voltage (Fig. 5b)

The probe potentials with respect to plasma must adjust themselves so that the basic current relations are still satisfied. Then the probe system assumes the potentials as shown in Fig. 5b . Probe No. 1 moves closer to plasma potential and collects more electrons, and probe No. 2 moves away from plasma potential and collects fewer electrons. The extra electrons flowing to probe No. 1 pass

through the circuit to make up the deficiency at probe No. 2 . All conditions are again satisfied and the system is located at some point b on Fig. 6.

(c) V_d = Somewhat larger negative voltage (Fig 5 c)

Probe No. 1 moves still closer to space potential and collects the entire electron current to the system since probe No. 2 is now so highly negative with respect to the plasma that no electrons can reach it. Half of the electrons reaching probe No.1 now pass through the external circuit to probe No.2. All conditions are satisfied and the system locates at some point y on Fig. 6.

Further increase in the negative value of V_d can cause no further change in the current distributions because probe No.1 already collects a sufficient electron current to balance the entire positive ion current flowing to the system. Consequently probe No. 1 remains fixed with respect to the plasma and probe No. 2 goes negative along with V_d. Probe No. 2 is saturated with respect to positive ions as system moves along the flat portion yx of Fig.6.

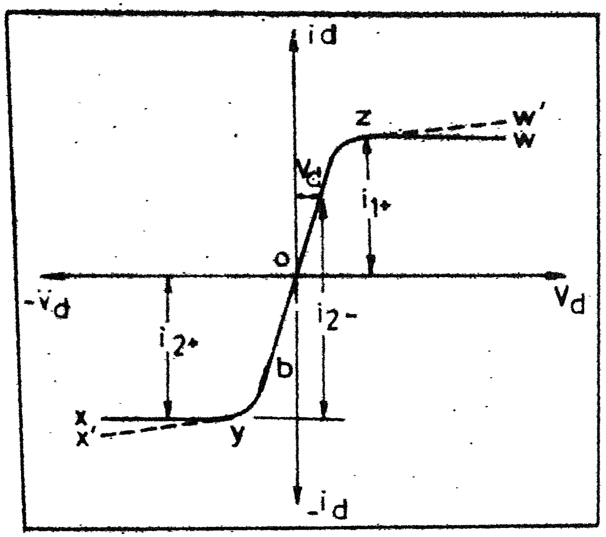
In practice one finds that this flat portion has a slight slope as shown by the dotted portion y x'. This slow increase is due to an expansion of sheath thickness as the probe goes increasingly negative with respect to the plasma.

The symmetry of the system will cause it to reverse the previous results when V_d is positive, giving portion ozw or ozw' . The flat portion zw or zw' corresponds to positive ion saturation current to probe No.1.

The total positive ion current to the system is simply the sum of the positive ion currents to both probes and so can be found by adding the magnitudes of the currents at y and z, as symbolised by i_{1+} and i_{2+} .

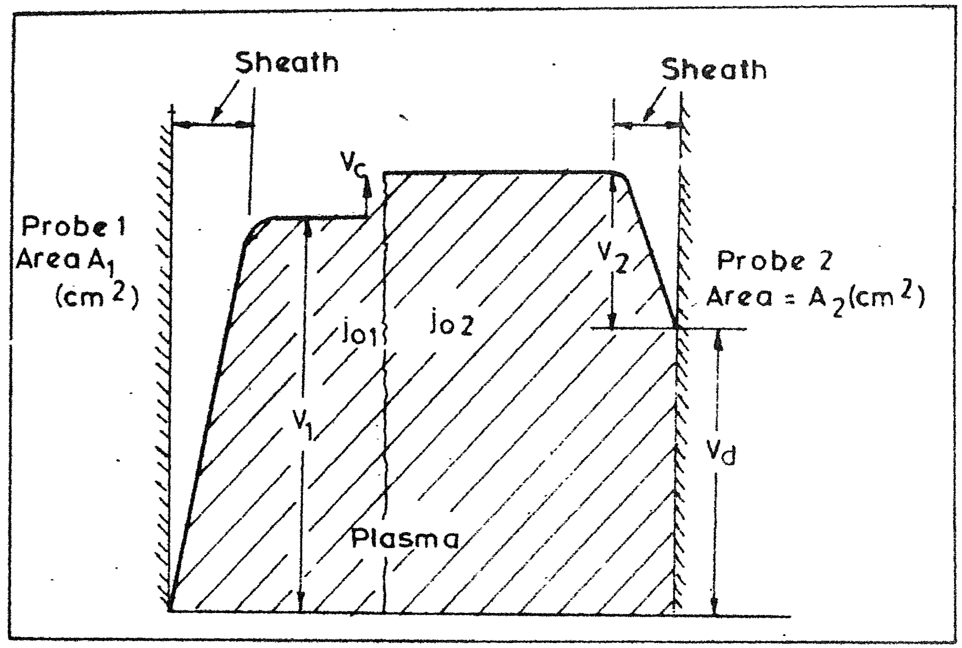
The electron current which flows from the plasma to probe No. 2 is simply the difference between the total space current (i_d) and the positive ion current to this probe. Thus the electron current i_{2-} to probe No.2 is given by

$$|i_{2-}| = |i_d| - |i_{2+}| . \qquad (3.17)$$



Ideal current-potential characterstic of the double probe

FIG. 6



Generalized schematic diagram for the use of the double probe

FIG. 7

3.7 Electron Temperature Determination

3.7.1 Logarithmic plot method:

A generalised potential diagram for the system of Fig. 4 is shown in Fig. 7 . The potentials V_1 and V_2 represent the voltages of the surrounding plasmas with respect to the corresponding probes. The potential V_c respresents any small difference in plasma potential which may exist between the regions surrounding the probes, plus the total contact potentials acting in the system. j_{o1} and j_{o2} are electron space current in the plasma adjacent to probe No. 1 and probe No. 2 respectively.

Since the net current to the system must be zero

$$i_{1+} + i_{2+} = I_+ = i_{1-} + i_{2-} . \qquad (3.18)$$

Substituting theequivalents for i_{1-} and i_{2-} in terms of Boltzmann relation, we obtain:

$$I_+ = A_1 j_{o1} \exp(-\phi V_1) + A_2 j_{o2} \exp(-\phi V_2), \quad (3.19$$

where

$$\phi = e/kT_e = 11600/T_e .$$

The potential diagram of Fig.7 fields:

$$V_1+V_c=V_2+V_d \text{ or } V_1=V_2+V_d-V_c . \qquad (3.20)$$

Substituting (3.20) into (3.19) and rearranging, we obtain:

$$\ln\left[\left(\frac{I_+}{i_{2-}}\right) - 1\right] = -\phi V_d + \ln\sigma = \ln\gamma , \qquad (3.21)$$

where

$$\gamma = (I_+/i_{2-})-1 \qquad (3.22)$$

and

$$\sigma = (A_1 j_{o1}/A_2 j_{o2}) \exp(\phi V_c) . \qquad (3.23)$$

Thus the plot of $\ln\gamma$ against V_d should yield a straight line whose slope is a measure of the electron temperature. It is to be noted that the slope of (3.21) is essentially unaffected by any of the factors included in σ ; viz., probe areas, electron random current densities, difference in plasma potential between probes, and contact potentials. For an unambiguous determination of T_e, the random current densities should not change with probe current. This is much more likely to be the case with the DPM than SPM since the current drain can be hundreds of times smaller in the former case. Thus DPM is inherently a more general

method. It can be used during or after the discharge and even when the plasma potential varies with time.

3.7.2 Equivalent resistance Method:

This describes another method by which T_e can be determined very quickly from i_d vs. V_d plots. Eq.(3.21) can be expressed as:

$$i_{2-} = \frac{I_+}{[\sigma \exp(-\phi V_d)+1]} \tag{3.24}$$

Taking the derivative of i_{2-} with respect to V_d and evaluating at $V_d = 0$, one obtains:

$$\left[\frac{di_{2-}}{dV_d}\right]_{V_d=0} = \frac{I_+ \phi \sigma}{(\sigma+1)^2} \tag{3.25}$$

Solving for T_e and substituting for $\frac{dV_d}{di_{2-}}$ its practical equivalent, $\frac{dV_d}{di_d}$, one obtains:

$$T_e = 11600 \frac{\sigma}{(\sigma+1)^2} \left[I_+ \frac{dV_d}{di_d} \right]_{V_d=0} \tag{3.26}$$

From (3.21) we can obtain

$$\sigma = \left[\frac{I_+}{i_{2-}} - 1 \right]_{V_d=0}$$

For convenience we introduce the factor G such that:

$$G = \left[\frac{i_{2-}}{I_+} \right]_{V_d=0} = \frac{1}{1+\sigma} . \qquad (3.27)$$

G can be obtained directly from the current-voltage characteristic. Substitution of (3.27) into (3.26) yields:

$$T_e = 11600(G-G^2) \left[I_+ \cdot \frac{dV_d}{di_d} \right]_{V_d=0} = 11600(G-G^2) . R_o . I_+ \qquad (3.28)$$

where

$$R_o = \left[\frac{dV_d}{di_d} \right]_{V_d=0} . \qquad (3.29)$$

The factor R_o is denoted as the equivalent resistance. Eq.(3.28) provides a rapid and convenient means of obtaining T_e directly from the V_d-i_d characteristic. Both the methods mentioned above will be illustrated in the sets of experimental data which will follow.

Since, in the equivalent resistance method one makes use of the slope of V_d-i_d curve at V_d=0, it would

be desirable to use the value of I_+ corresponding to this point when computing T_e from Eq. (3.28) . It is found that [5] for all practical purposes, if V_d-i_d characteristic is reasonably symmetrical, one is safe in extending the lines x' y and w'z (see Fig.6) to a factor 0.8 of the distance between the point where the saturation begins and the point where the extrapolated saturated portion intersects with V_d=0 axis and then horizontally the rest of the way. From these extended curves one can obtain the value of I_+ corresponding to V_d=0. An illustration of this method is given in the following chapter.

3.8 Floating potential:

The potential V_f is the potential at which an isolated probe or a bit of isolated wall draws no net current, i.e., when both i_+ and i_- flowing to a probe are equal. An approximate expression for floating potential V_f (with respect to space potential) is given by [33] :

$$V_f = \frac{kT_e}{2e} \ln \left[\frac{T_e}{T_i} \frac{M}{m_e} \right] \qquad (3.30)$$

where T_i is the ion temperature , M is the atomic mass of the gas in the discharge tube, and m_e is the electronic rest-mass. The value of V_f allows additional information to be gained. From the values of i_+, T_e and, V_f we can evaluate electron density (n_-), details of which follow in the next section.

3.9 Determination of electron and ion densities:

Neither SPM nor DPM are suited for the determination of the electron density n_-. It is impossible to saturate the electron current to the probe unless its area is extremely small. But the situation is not completely hopeless, however. In order to determine n_- and n_+ , it is merely necessary to set a value on one unknown, the positive ion temperature T_i. The value of T_i in low pressure gas discharges is very close to T_g, the gas temperature. In addition, as will be seen, n_- and n_+ vary as the square root of T_i . Thus, errors in selecting a value for T_i will have a much smaller effect on the values of n_- and n_+.

We set:

$$j_+ = n_+ e\, c_{av}, \qquad (3.31)$$

where c_{av} is the average drift velocity of the ions.

In the unstable plasmas, where space-charge fields are extremely small, c_{av} must be due almost to the outward motion from the plasma into the sheath arising from the random motion of the ions. In that case $c_{av} = \frac{1}{4}\bar{c}_+$, where $\bar{c}_+$ is the ion velocity averaged over a Maxwellian distribution. Then:

$$n_+ = 4j_+/e\bar{c}_+ \qquad (3.32)$$

where j_+ is the random ion current density, but:

$$j_+ = i_+/A_s \qquad (3.33)$$

where i_+ is positive ion current to probe, and A_s is the sheath area.

Estimates made by the method of Langmuir and Mott-Smith [1] indicate that at the points y and z of Fig.6, the positive ion current to the probe is space-charge limited but that the sheath area may be appreciably larger than the probe area.

Making the substitution $\bar{c}_{+}=1.87\times10^{-8}(T_{+}/M)^{\frac{1}{2}}$ we obtain:

$$n_{+}=(1.34\times10^{27}/A_{s})i_{+}(M/T_{+})^{\frac{1}{2}} \qquad (3.34)$$

Where M is the mass of a positive ion.

To determine A_s we make use of space-charge limited current equation for cylindrical diodes [34]

$$i_{+}=14.66\times10^{-6}(m_{e}/M)^{\frac{1}{2}}\frac{l_{p}V^{3/2}}{r_{p}\beta^{2}} \qquad (3.35)$$

Where V is the difference in potential between the probe and the plasma, l_p is the length of the probe, r_p is radius of the probe, and β^2 is a known function [35] of (r_s/r_p), r_s being the radius of the sheath.

To obtain V, we recall that when the probe is at wall potential (i_d=0) its potential with respect to the plasma is V_f. As i_d varies from zero to the saturation value of i_{1+}, i_{2-} changes by a factor of about 2. The probe-space potential must then decrease by an amount determined from the Boltzmann relation:

$$0.5=\exp\left[\frac{11600}{T_e}.\delta V\right]$$

Therefore
$$\delta V = -\frac{T_e}{11600}\times0.693 \qquad (3.36)$$

Then:
$$V= V_f+\delta V. \qquad (3.37)$$

Using Eqs. (3.35) and (3.37) we can calculate the value of β^2. Then making use of the table (See Appendix B) given by Langmuir and Blodgett [35] we can predict the value of $\frac{r_s}{r_p}$, from which A_s can be calculated. Then using Eq.(3.18) we can calculate the number density of ions. If we assume $n_-=n_+$, which is possible in experiments, we can have number density of electrons.

However, it is to be noted the values of n_- so obtained are not very reliable. V_f can not be calculated accurately and since V_f appears in an exponent, small errors in V_f give large changes in n_-. The method is useful in giving orders of magnitude and may be reliable within a factor of 5 or so.

CHAPTER IV

DESCRIPTION OF THE EXPERIMENTAL SET UP

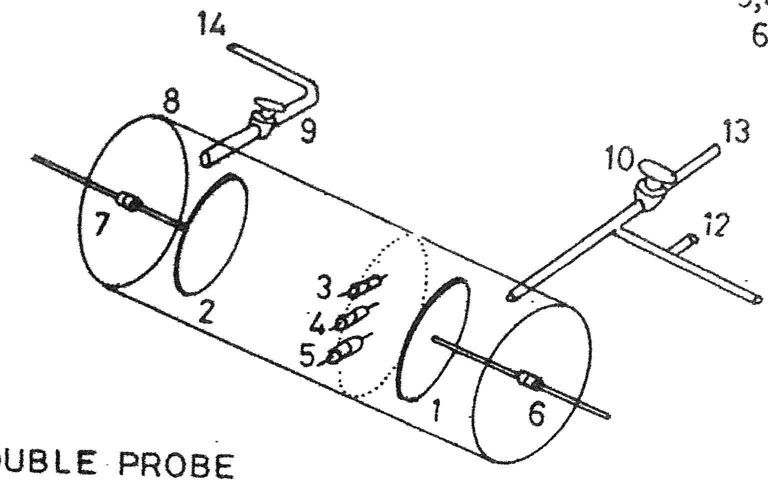
4.1 Experimental set up.

The proposed study of the plasma diagnostics in gas discharges using the double probe method was carried out in two different discharge tubes, designated as Tube No.1 andTube No.2. Tube No.1 is used for diagnostics without external magnetic fields and Tube No.2 is used for diagnostics in magnetic fields.

4.1.1 Discharge tubes and the probe system:

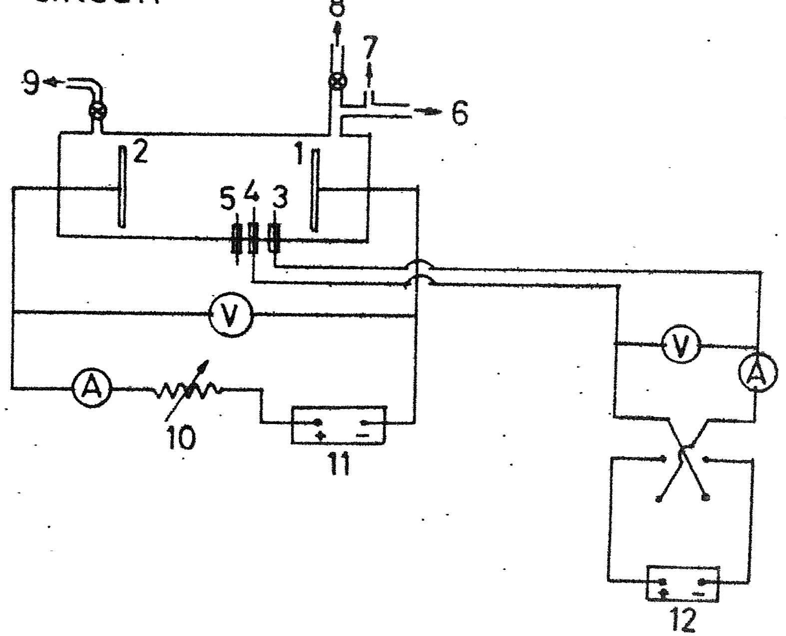
Fig.8A presents the schematic diagram of Tube No.1. It is a pyrex glass tube of cylindrical shape and provision is made through glass and rubber tube for connections to the vacuum pump, the Pirani gauge, the manometer and the gas cylinder. The details of the tube dimensions are given in Table 1. Thin circular plates (Table.1) of nickel were used as the electrodes. They were point-welded to thick tungsten wires and then glass-tungsten seal was made to fix them to the glass tube coaxially.

(A) DISCHARGE TUBE No. 1



1 ANODE
2 CATHODE
3,4,5 PROBES
6,7 GLASS-TUNGSTEN SEAL
8 PYREX GLASS TUBE
9,10 VACUUM VALVES
11 TO MANOMETER
12 TO PIRANI GAUGES
13 TO VACUUM PUMP
14 TO GAS CYLINDER

(B) DISCHARGE & DOUBLE PROBE CIRCUIT



1 ANODE
2 CATHODE
3,4,5 PROBES
6 TO MANOMETER
7 TO PIRANI GAUGE
8 TO VACUUM PUMP
9 TO GAS CYLINDER
10 BALLAST RESISTANCE
11 DC POWER SUPPLY ($\pm$3000V, 25mA)
12 DC POWER SUPPLY ($\pm$60 V, 1A)

FIG 8

TABLE NO.1

Details of the discharge tubes

Description	Tube No.1	Tube No.2
Material	Pyrex glass	Pyrex glass
Length	16 cm	8.5 cm
Inner diameter	5.8 cm	5.6 cm
Electrode material	Nickel	Aluminum
Electrode spacing	10.9 cm	5.5 cm
Electrode diameter	4 cm	3.95 cm

TABLE No.2

Details of the Probe system

Description	Tube No.1	Tube No.2
Number of probes	3	2
Probe material	Tungsten	Tungsten
Probe diameter	15 mil	20 mil
Probe length*	0.3505 cm(3) 0.3085 cm(4) 0.351 cm(5)	0.289 cm (3) 0.258 cm (4)
Probe spacing	$\approx$0.5 cm	$\approx$1 cm

* The figures in the brackets represent the position of the probes as given by Fig.8A and 9 respectively.

The electrodes are approximately parallel to each other. Vacuum purpose glass valves are used in gas and vacuum pump lines. Three tungsten wires of 15 mil diameter are used as the probes. Each probe has a glass sleeve and exposes a small tip into the discharge tube. All the three probes are fused (3cm away from the anode) to the discharge tube wall and all of them are contained in a plane parallel to the electrode dises. This arrangement is done to reduce the differences in potential which each probe experiences in its vicinity and this geometry makes them pass through equipotential surfaces of the positive column. They are separated by a distance of 5 mm and the probe dimensions are given in Table No.2.

Tube No. 2 is a small tube(Fig.9) specially designed to fit between the pole pieces of the electromagnet used in the present study. It contains thin circular plates of aluminum material and they are fixed at the ends of the tube using Araldite. Araldite seal can hold vacuum up to 10^{-3} torr and the experiment is done at much higher pressures than this value. It also has provision for

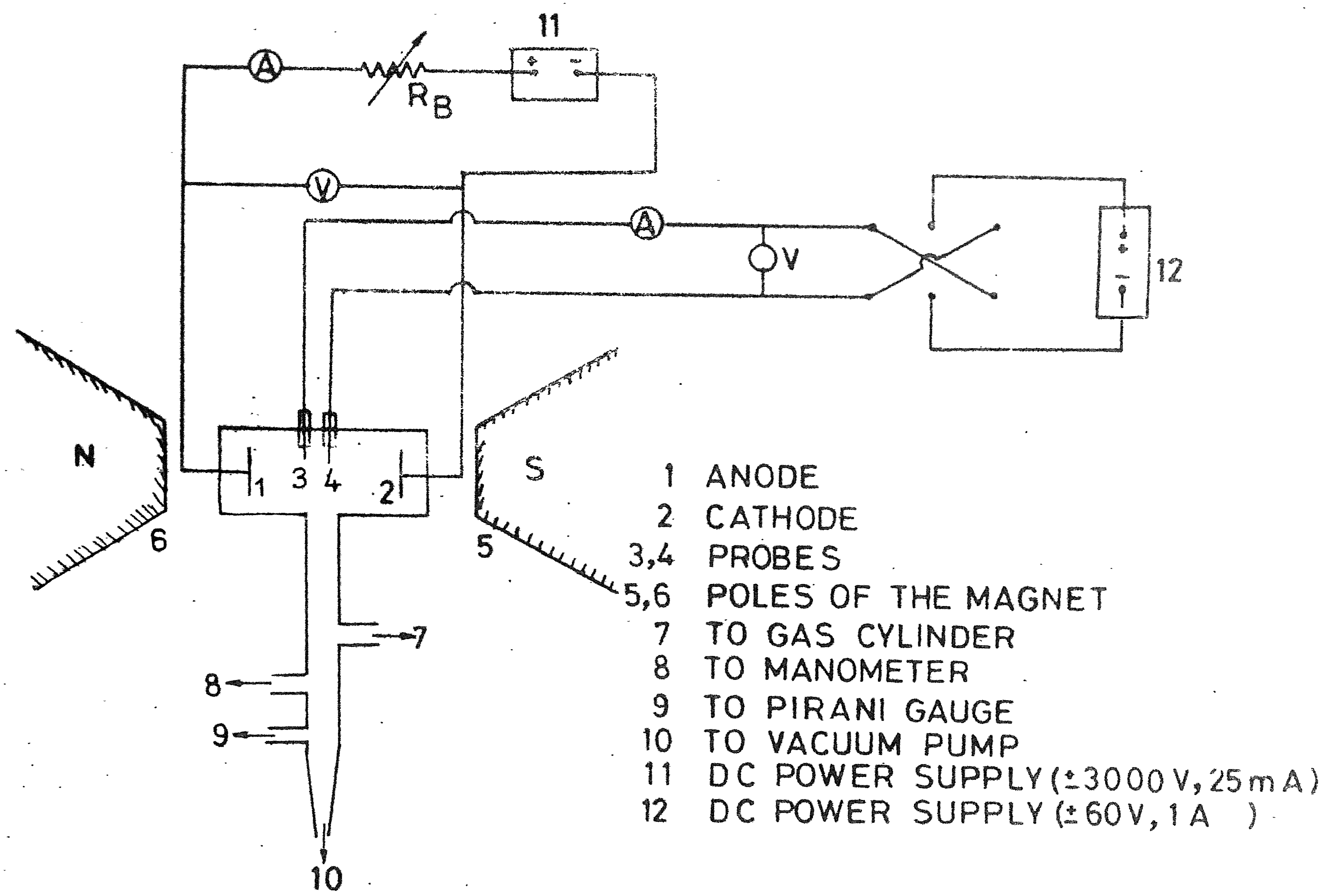


FIG. 9 DISCHARGE TUBE No.2 AND ITS CIRCUIT USED FOR DIAGNOSTICS IN MAGNETIC FIELD

vacuumpump, manometer, Pirani gauge and gas cylinder connections. It has only two probes, and each is a tungsten wire of 20 mil diameter. The probes are spaced 1 cm from each other and they are also fused in the middle of the pyrex glass tube in such a way that the plane containing the probes is parallel to the electrode discs. Probes have glass sleeves on them and expose a small tip for diagnostic purposes. Discharge tube dimensions are given in Table No.1 and probe dimensions are given in Table No.2.

Two other tubes of brass and copper electrodes have also been fabricated but could not be used in the present experiment due to the lack of time in the course of this study. They have one electrode fixed and a movable electrode. The electrode separation can be varied using a mechanical bellow system available in the laboratory. Each tube contains a pair of probes, which will help the diagnostic study of the gas discharges in that tube.

4.1.2 Instrumentation:

(a) Establishment of the discharge

DC power supply of ± 3000V and 25mA has been used as the high voltage source. To control and with-stand the discharge currents in the range of our study (0.5mA-20mA), a ballast resistance of 65 Kilo ohms and 20 W was used. With this resistance in circuit it was convenient to establish a stable glow discharge and hold the current in the above mentioned ranges.

(b) The probe circuit (Fig. 8B and 9)

A low voltage dc power supply of ± 60V and 1A has been used to bias the probe voltages. In the probe circuit no resistance was used since it is not necessary.

(c) Current and voltage measurements

In the discharge circuit (Figs.8B and 9) multimeters have been used to measure the current and voltage between the electrodes after establishing

the glow discharge. In the probe circuit also multimeters have been used for measuring the differential probe voltage, V_d and the circuit current , i_d.

(d) Production and measurement of the magnetic field

A 200V, 5A variable dc power supply has been used to supply current to the coils of the magnet. The electromagnet has maximum pole separation of 10 cm and pole diameter of 10 cm. The magnetic field strength has been measured using a sensitive Bell gause meter with a transverse Hall probe.

(e) Vacuum generation

Hind-Hivac rotary pump has been used to evacuate the discharge tubes. The lowest pressure obtained was 0.03 torr, which is sufficient for probe studies.

(f) Pressure measurement

A Hind-Hivac Pirani gauge and a manometer have been used for monitoring the pressures in the discharge tubes. All the pressure readings in

this experiment have been measured by the Pirani gauge; however, a manometer is incorporated to have a check between the readings and for safety reasons when filling the tube with a gas from a high pressure cylinder.

All the discharge tubes and the manometer are fabricated in the Glass Blowing section and aluminum, copper and brass electrodes are machined from the commercially available metal rods in the Nuclear Engineering work shop . The whole experimental set up has been erected in the new Plasma Science Laboratory.

3.2 Experimental procedure

Before mounting the discharge tubes to the working table, they were thoroughly cleaned using Acetone and Hexane. All the electrodes were polished resulting in smooth surfaces. Probes are initially chemically cleaned and later when the discharge is established, they were electrically cleaned, i.e, by applying a high voltage between the probes when

TABLE NO.3

Conditions of the experimental study

Description	Tube No.1	Tube No.2
Type of study	without magnetic fields	with magnetic fields
Gases	Argon, Hydrogen, Nitrogen, Air	Argon, Air
Discharge currents	0.5mA–20mA	5mA
Pressures	0.05–0.5 torr	0.05–0.5 torr
Magnetic field strengths	—	100–1200G

the main discharge current is high.

The experimental ranges and the conditions under which the present study has been carried out is given in Table No.3 in a concise form. Initially the tube is evacuated up to about 0.03 torr and then the gas is injected into the tube. After several such evacuations and gas injections, being done alternatively, tube was used for taking experimental data. Pressure in the discharge tube is controlled finely by a needle valve which is in the gas line connection.

Then a large voltage is applied between electrodes and a glow discharge is established, after which the system is left for some time in that condition so that the impurities sticking to the walls of the tube, electrodes, probes and other materials are eliminated.

Two serious difficulties were faced in doing this study with the double probes:

(a) Study above 0.5 torr was impossible since double probe draws very low current from the discharge and it could not be detected with the ordinary multimeters used in the experiment. Attempts were made to measure such currents with a sensitive electrometer, which can measure currents from 10^{-9}A to 10^{-12}A, but these failed because it needed a special circuit design which could not be done during the course of this study.

(b) Main region of discharge of interest in this study was the positive column for which we can evaluate the electron temperatures and the number densities theoretically using Eq. (3.16). But unfortunately at some pressures in some gases positive column could not be obtained, reasons for which are explained in the previous chapter. More over, since the probe system is static, it could not be always placed in the positive column, even when the latter appears. So the whole of our study ranges in the positive column, negative glow and some times in dark spaces. No well established

theory is available, unlike the positive column, for the phenomena in the negative glow and the dark spaces. Hence for a check on our experimental results, we evaluated electron temperatures at all pressures assuming that the positive column exists, which should not be taken too seriously for comparison.

Study with magnetic fields is done under three different conditions. Magnetic field is applied coaxially to the tube No.2 with E and H parallel and anti-parallel. Then tube No. 2 is rotated 90° around the glass tube which is meant for different connections so that E is perpendicular to H. When E is perpendicular to H the directions of the fields are adjusted in such a way that $\vec{E}\times\vec{B}$ drift causes the positive column press towards that side of tube wall on which probes are fixed.

In each of these experimental conditions (Table 3) differential probe voltage is varied between $\pm$ 60V and the current is measured point by point. A series of experimental characteristics were obtained from which the electron temperatures are evaluated. The details of calculations are given in the next chapter.

CHAPTER V

RESULTS, DISCUSSION, AND RECOMMENDATIONS

5.1 Results and discussion

The results of the present investigation are given in the form of graphs and tables. The following subsections discuss some of the important details.

5.1.1 DPM in the evaluation of electron temperature

The presentation of the data which follows is mainly intended for the purpose of illustrating the use of the DPM and in comparing the results of the electron temperatures obtained from various methods. Probe characteristics obtained at different discharge currents of argon at 0.1 torr in Tube No.1 are illustrated in Fig.10 where the probe current increases with the increase in the main discharge current. The probe characteristics obtained have considerable slopes in the saturation regions, reasons for which are already discussed in chapter 3. Due to these large slopes temperatures were evaluated from these characteristics,

using the methods given by Johnson and Malter [5] Yamamoto and Okuda [10] , and Rohatgi [13] , and compared these with each other. An illustrative example follows.

(a) Equivalent resistance method(ERM)

Fig.11 shows the probe characteristic obtained at a discharge current of 5mA of argon at 0.1 torr in Tube No.1 . The saturated portions are extended as suggested by Johnson and Malter [5]and I_+ at $V_d=0$ is obtained.

$$(I_+)_{V_{d=o}} = 0.3+0.425=0.725\ \mu A$$

$$G= \left(\frac{i_{2-}}{I_+}\right)_{V_d=o} = \frac{0.275}{0.725} = 0.379$$

Slope at $V_d=0$ is obtained by drawing a tangent to the characteristic at which $V_d=0$; from which we get

$$R_o= \left(\frac{dV_d}{di_d}\right)_{V_d=0} =8.744 .$$

Hence T_e is evaluated from Eq.(3.28) and the value obtained for $T_e= 1.73\times10^4 K$. σ is computed using Eq.(3.27).

$$\sigma = (\frac{1}{G} -1)=1.639$$

Similarly T_e was evaluated for discharge currents of 10mA, 15mA, and 18mA at 0.1 torr of argon in Tube No.1 using Figs. 13, 15, and 17 respectively. The values of T_e and σ obtained are given in Table.4 and 5 respectively.

(b) Logarithmic plot method (LPM)

The plot of the function ln $[\frac{I_+}{i_{2-}} -1]$ against ΔV_d is presented in Fig.12. In Fig.12, V_d is the voltage change necessary to make ln $[\frac{I_+}{i_{2-}} -1]$ change in the ratio 2.73:1. T_e obtained from this method is 2.13×10^4K and is 1.65. σ obtained here agrees very well with the σ obtained by ERM.

Similarly T_e was evaluated for discharge currents 10mA, 15mA, and 18mA at 0.1 torr of argon in Tube No.1 using Figs 14, 16, and 18 respectively. The values of T_e and σ obtained from this method are given in Table 4 and 5, respectively.

(c) Method given by Yamamoto and Okuda [10] (Y-O)

From Fig.11 S=slope of the saturated portion at large V_d
$=0.028\ \mu A/_V$

$$A = \frac{(I_+)_{V_{d=0}}}{2} = \frac{0.3+0.425}{2} = 0.3625\ \mu A.$$

Hence T_e is evaluated from Eq. (2.7) :

$$T_e = 5800 x 0.3625 x \left[\frac{1}{8.744} - 0.014 \right]^{-1} = 2.09 x 10^4 K.$$

Using this value of T_e the criterion as given by Eq.(2.6) for the double probe method has been checked:

$$0.693 x \frac{S}{\phi} = \frac{0.693 x 0.028}{0.5537} = 0.035 \ll 0.3625.$$

Hence Eq (2.6) is satisfied and it means that the probe characteristic has a saturated portion, but with a slope, for which correction is necessary to evaluate T_e. Similar calculations for other discharge currents have been done and they are given in Table No.4 under the column Y-O.

(d) Method given by Rohatgi [13]: (ROH)

We made use of the Eq.(2.8) and evaluated T_e from it:

$i_p = 0.35\mu A.$

$$\left(\frac{dV_d}{di_d}\right)_{V_d=0} = 8.744 .$$

Therefore, $T_e = 5797.1 \times 0.35 \times 8.744$

$= 1.77 \times 10^4 K.$

Similarly T_e was calculated for other discharge currents and represented in Table No.4 .

An observation at Table No.4 and 5 reveals that all the methods of evaluating T_e are almost consistent with each other and especially there is a a marked agreement in results between ERM and ROH ; and LPM and Y-O methods.

We used Eq. (3.16) to evaluate T_e theoretically. Eq. (3.16) is a nonlinear equation and it needs a numerical method to evaluate T_e. We used successive approximation method to evaluate T_e from Eq. (3.16). T_e has been computed for different pressures in different gases and for the two discharge tubes used. A computer program has been written for this purpose

and this computation has been done on DEC-1090 computer system. The program is given in Appendix. C. This value of T_e for 0.1 torr is represented in the column 'theoretical' in Table No.4. Since this Eq.(3.16) is independent of the discharge current we have only one value of T_e in this column.

The experimental results are reasonably in good agreement with this value. Since all these methods are giving almost same results, for further calculations, including the magnetic field study , we used the equivalent resistance method to evaluate T_e .

Using the above method, evaluation of T_e was done on a series of data which has been taken using Tube No.1 at different discharge currents in argon, hydrogen, nitrogen and air. We now present the results in Table Nos. 6-9. However, for air the theory discussed in section (3.3) does not hold because of its electronegative behaviour. But there is no theory available to substantiate our experimental results. But we present

them in Table No.9 to observe whether Johnson-Malter method is applicable . and it is found that DPM works very well even for the electronegative gas discharges.

5.1.2 Evaluation of the number densities:

To evaluate n_- experimentally we mainly made use of the method described in section 3.9 . For evaluating the floating potential, V_f we used Eq(3.30) and the calculated values for nitrogen are given in Table. No.10 for observation. The floating potential is a few tens of volts and its values are ranging from 8-25 volts.

After evaluating the floating potential we carried out calculations for computing n_- from the theory discussed in section 3.9. A sample calculation of n_- for nitrogen at 0.08 torr and at a discharge current of 20 mA is shown below.

V_f=21V, T_e= 32847K.

V as calculated from Eq.(3.37) is 19.2V.

Then using Eq (3.35) β^2 is calculated;

$$\beta^2 = 23.655$$

Then using the table given in Appendix B, and using this value of β^2 [35] we interpolated the value of $\frac{r_s}{r_p}$ and the area of the sheath, A_s is computed to be:

$$A_s = 0.3258 \text{ cm}^2.$$

Hence using Eq.(3.34) n_- can be computed and the computed value of n_- is

$$n_- = 6.89 \times 10^9 \text{ cm}^{-3}.$$

Thus for each pressure, discharge current and for different gases in Tube No.1 we calculated the values of n_- and they are tabulated as shown in Table Nos.11-13. All these number densities are ranging from 10^8-10^{10} cm^{-3} which are consistent with literature value in low pressure gas discharges.

To evaluate n_- semi-theoretically, we made use of the positive column theory and utilised the charge distribution expression as given by Eq.(3.12).

We write Eq. (3.12) here again as

$$n_r = n_o J_o(2.405\ r/R).$$

We need to know the value of r and n_o. In our experimental tube, probes are situated 1.3 cm off the axis of the discharge tube. Hence r= 1.3 cm. and the radius of the discharge tube No.1 is 2.9 cm. To know the value of n_o, the electron density at the axis , we followed a procedure as described below.

B.E.Cherrington [39]has given an expression relating the current through the discharge, electron densities at the axis and the tube radius. The expression is

$$I=1.36\ n_o R^2 \mu_e Ee, \qquad (5.1)$$

where I is the discharge current, n_o is the electron density at the axis of the tube, R is the radius of the discharge tube, μ_e is the electron mobility (a function of E/p) and E is the electric field. If we know the temperature T_e, at some particular discharge current, then using Einstein's equation

$$\frac{D_e}{\mu_e} = \frac{kT_e}{e} \qquad (5.2\ )$$

we can find the value of $\frac{D_e}{\mu_e}$, where D_e is the diffusion coefficient of electrons . Huxley and Crompton [40] have plotted $\frac{D_e}{\mu_e}$ and W against E/N for argon, where W is the drift velocity and N is the number of atoms or molecules in the gas. From their plots we can get the values of W for different values of D_e/μ_e. But W is nothing but E . This value of W is substituted in (5.1) and n_o can be evaluated. Then using Eq.(3.12) we can get the value of n_r. These values of n_r are compared with the number densities obtained by the method described in section 3.9, are given in Table No. 11.

However, the values obtained by the former method are an order of magnitude lower than those obtained by the latter mathod. This discrepancy may be attributable more to the approximations involved in the former method. But the values obtained from each method are not showing too much variation. Since the data is available only for argon, the latter method could not be applied to other gases.

5.1.3 Electron temperatures and densities in the presence of magnetic fields:

In this part of the study Tube No.2 is used for diagnostics. Tables 14, 15 and 16 show some of the experimental results obtained during this study. T_e and n_- are computed from the methods as mentioned in chapter III. However, the data available from this study is not sufficient to draw any conclusions, since for most of the data obtained, probe characteristics were not in proper shape and so there were large errors in evaluating the electron temperatures and number densities. But however there is trend of decreasing temperature in the vicinity of the probes when E and H are anti-parallel and increasing temperatures when E and H are parallel. This discrepancy could be because of the non uniformity in the fields. It may be remarked that the trend observed for the anti-parallel case is as expected. Moreover the number densities obtained are showing good trend. As the

field is increasing number density at vicinity of the probes are decreasing since the coaxial field restricts the diffusion of charged particles towards the walls and hence the probes.

In the case when E is perpendicular to H, number densities are decreasing as the field H increases. This is quite agreeable because when E is perpendicular to H, the $\vec{E}\times\vec{H}$ drift causes the discharge regions to press against the wall and the regions are also constricted. So as the field H increases, the regions move away from the probe since the probe system is off the wall. Hence the probe experiences a low number density in its vicinity.

Results in this part of the experiment are some what unsatisfactory because of lack of sophistication in the experiment to study diagnostics in magnetic fields. When the magnetic field is applied it introduces oscillations and much more fast techniques are needed to get the probe characteristic in a short

duration . Further, much more theoretical study of the probes in magnetic fields is also needed to analyse the experimental data, which can be done as a continuation of this work.

5.2. Recommedations for future work:

The following recommendations for further investigations are made:

(i) A discharge of higher than 20 mA current should be studied with the double probes. Then the double probe system can draw sufficient current and good probe characteristics can be obtained.

(ii) A circuit should be designed to incorporate an electrometer so that small probe currents also could be measured efficiently.

(iii) Still longer discharge tubes should be fabricated so that a positive column of good stretch can be obtained. But this means that we need a higher voltage source than the one used in our experiment.

(iv) A movable probe system should be fabricated so that it can always be placed in a positive column.

(v) Vacuum pump of much higher capacity should be used so that the tube can be evacuated to a to a highest degree which will reduce the number of impure gas molecules.

(vi) A probe sweep circuit should be designed so that measurements caould be obtained in a short duration which will minimize the errors.

(vii) To check the results of probe studies much sophisticated techniques for example, microwave diagnostics must be used.

(viii) A detailed theoretical review of probe studies in magnetic fields should be done to interpret the results, which could not be done during the course of this study.

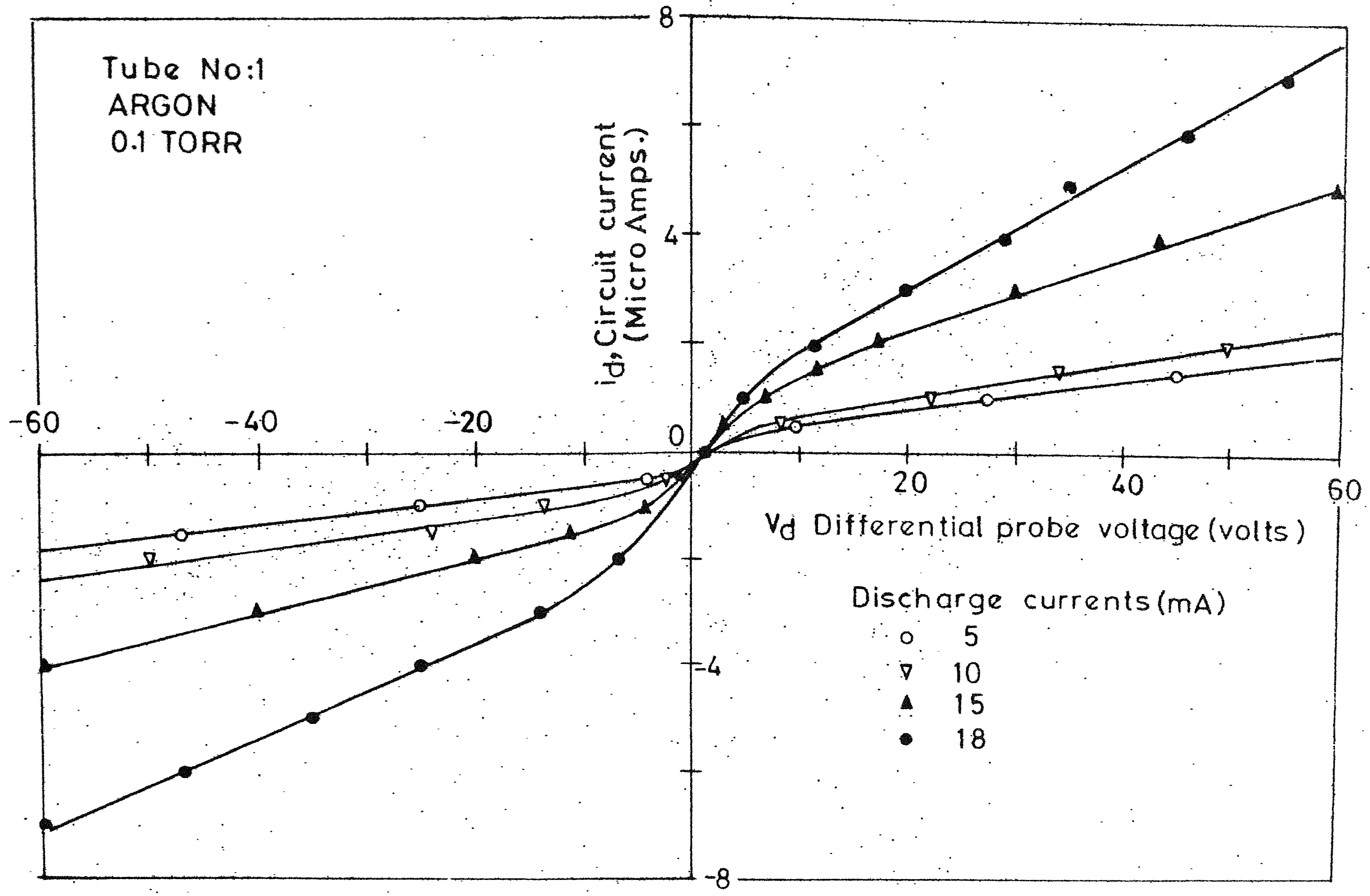


FIG.10 PROBE CHARACTERISTICS AT DIFFERENT DISCHARGE CURRENTS

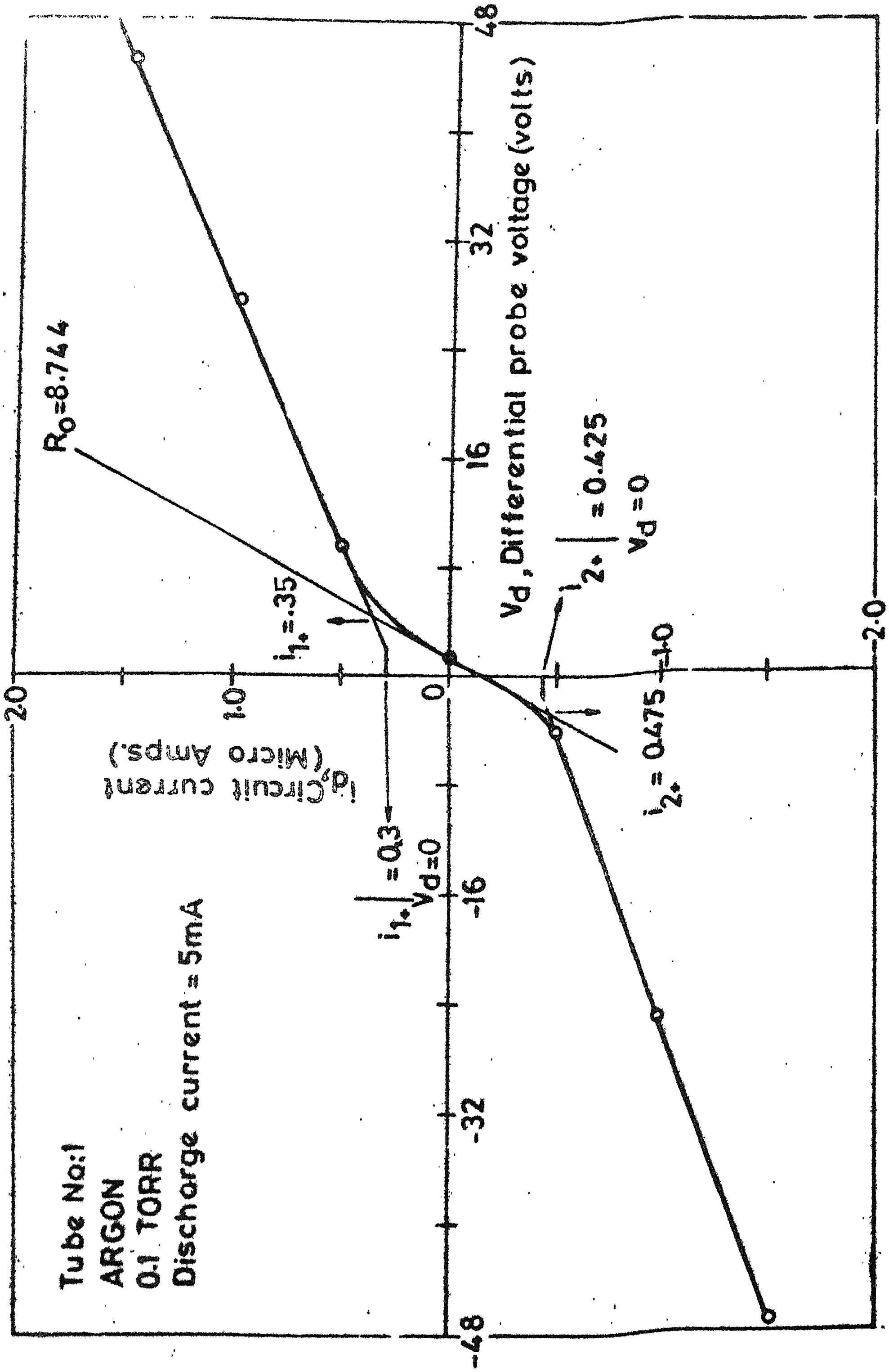


FIG. 11 DOUBLE PROBE CURRENT-VOLTAGE CHARACTERISTIC

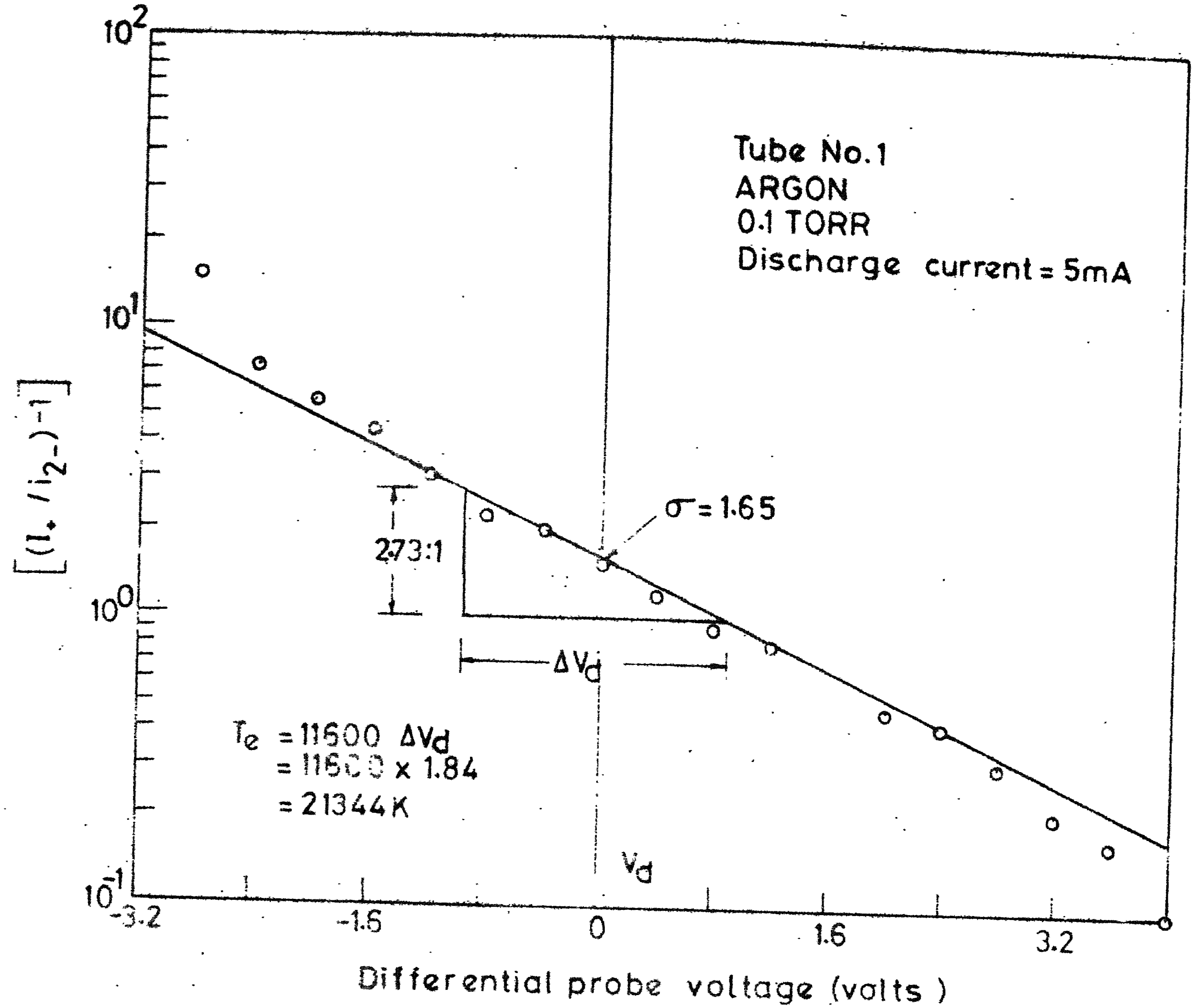


FIG. 12 TEMPERATURE DETERMINATION BY LOG PLOT METHOD

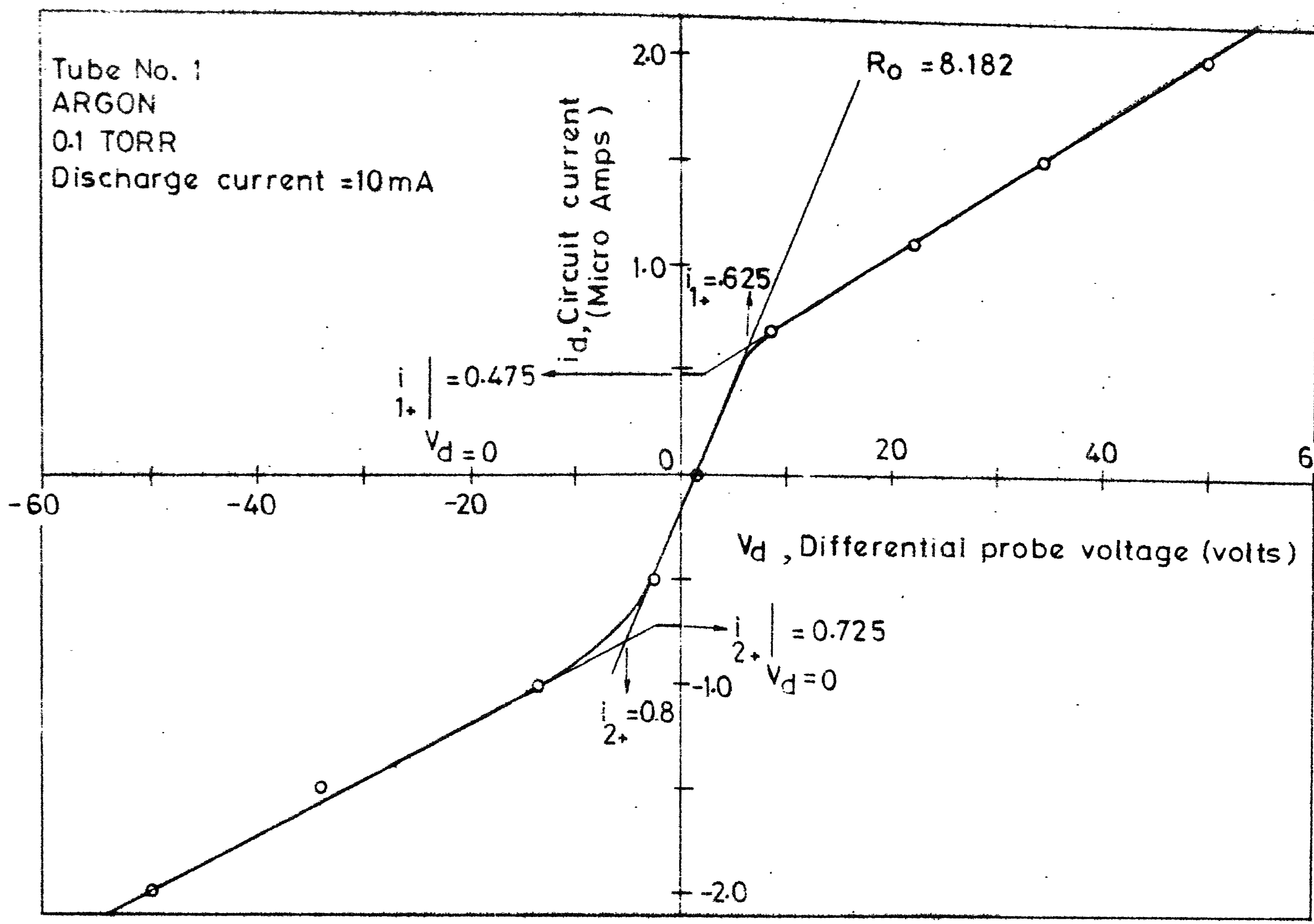


FIG.13 DOUBLE PROBE CURRENT-VOLTAGE CHARACTERISTIC

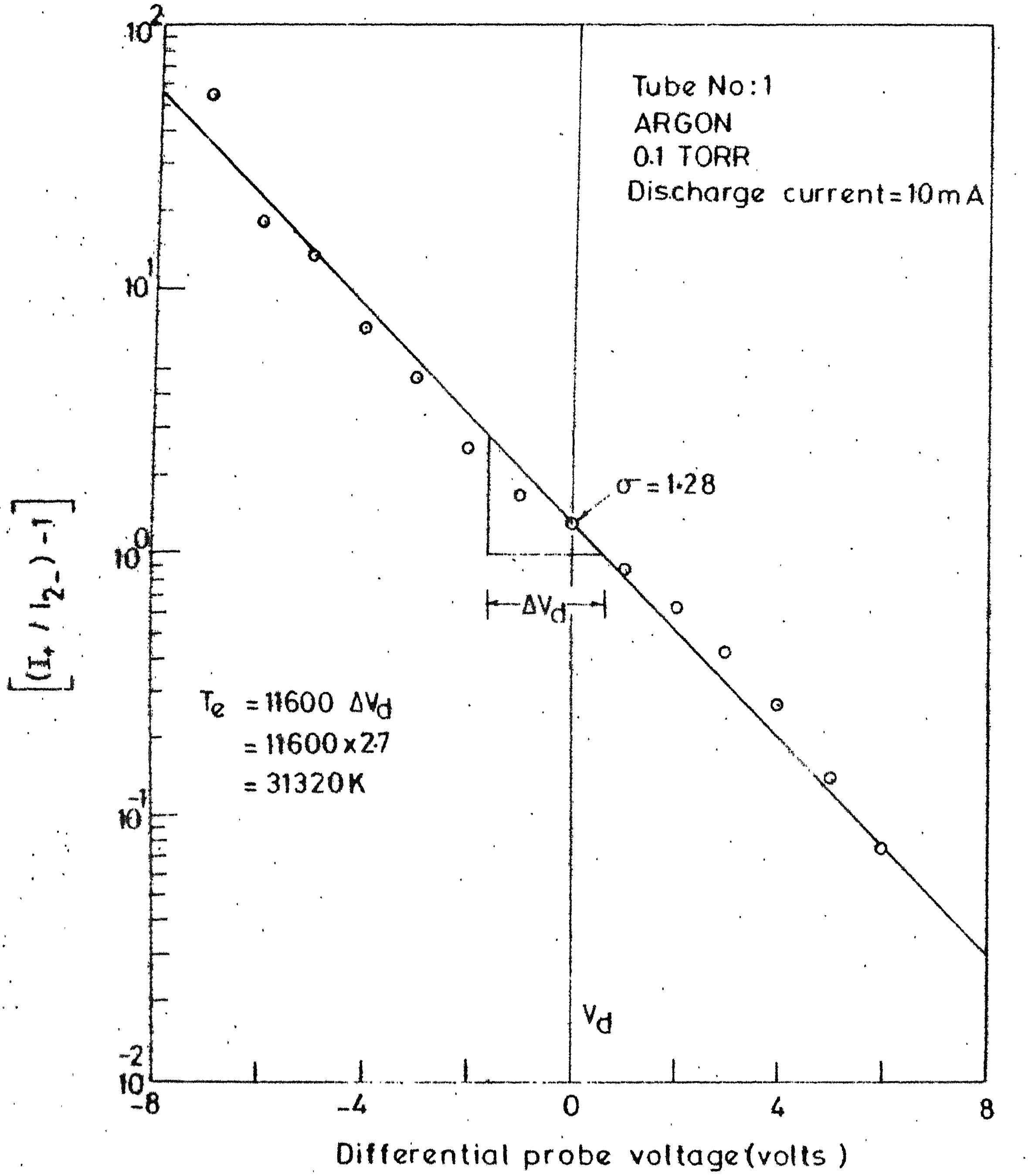


FIG.14 TEMPERATURE DETERMINATION BY LOG PLOT METHOD

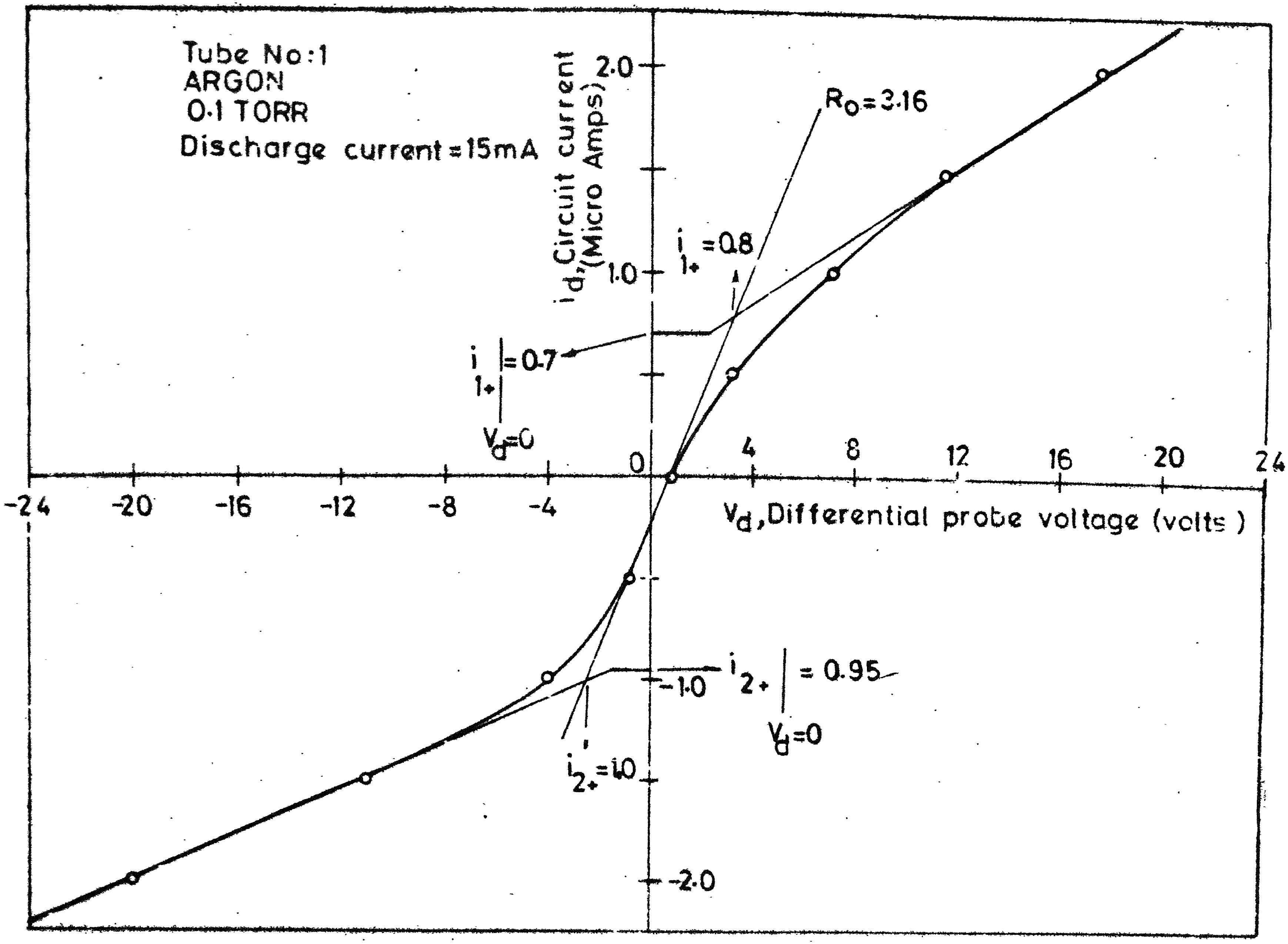


FIG. 15 DOUBLE PROBE CURRENT-VOLTAGE CHARACTERISTIC

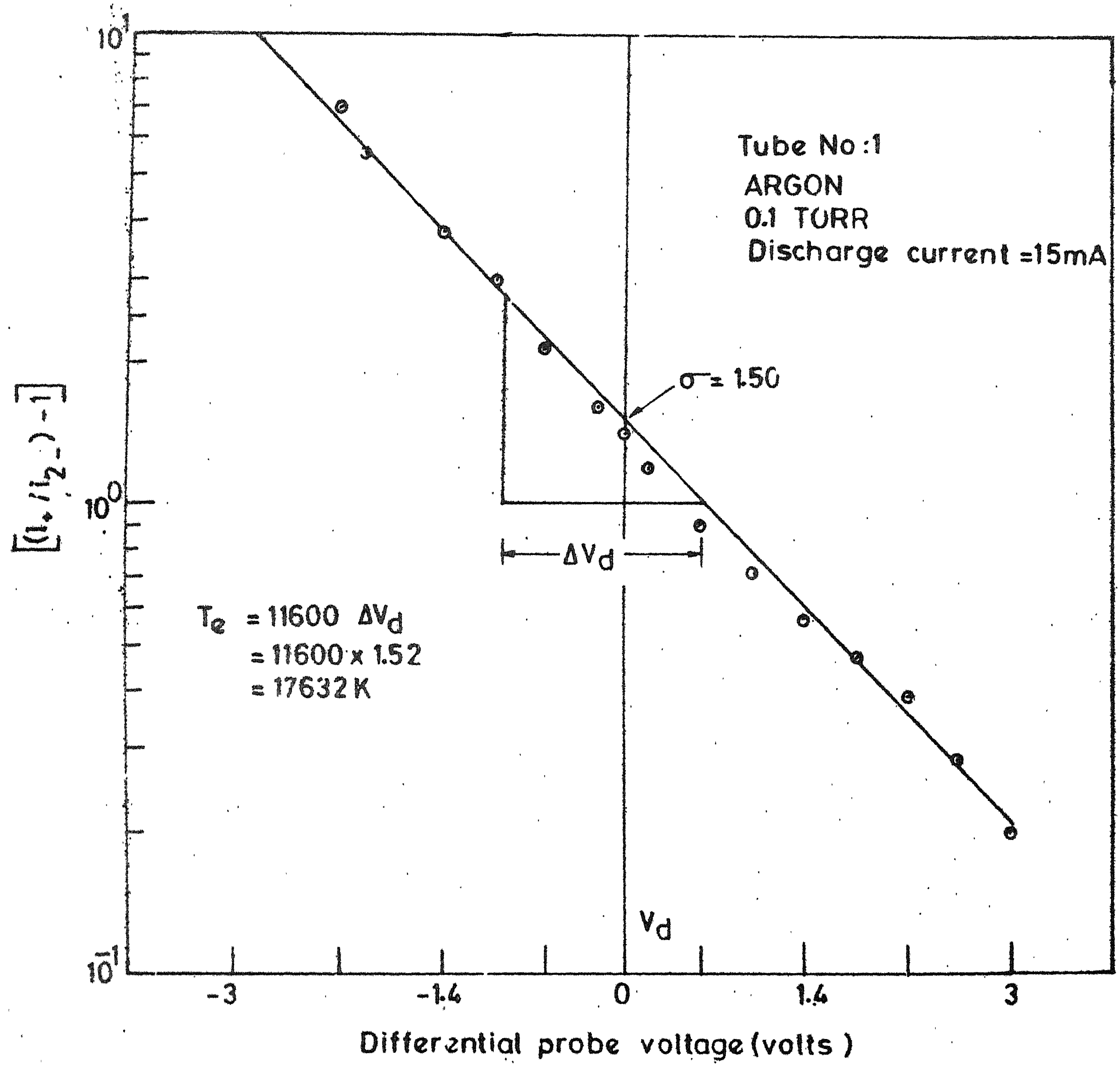


FIG.16 TEMPERATURE DETERMINATION BY LOG PLOT METHOD

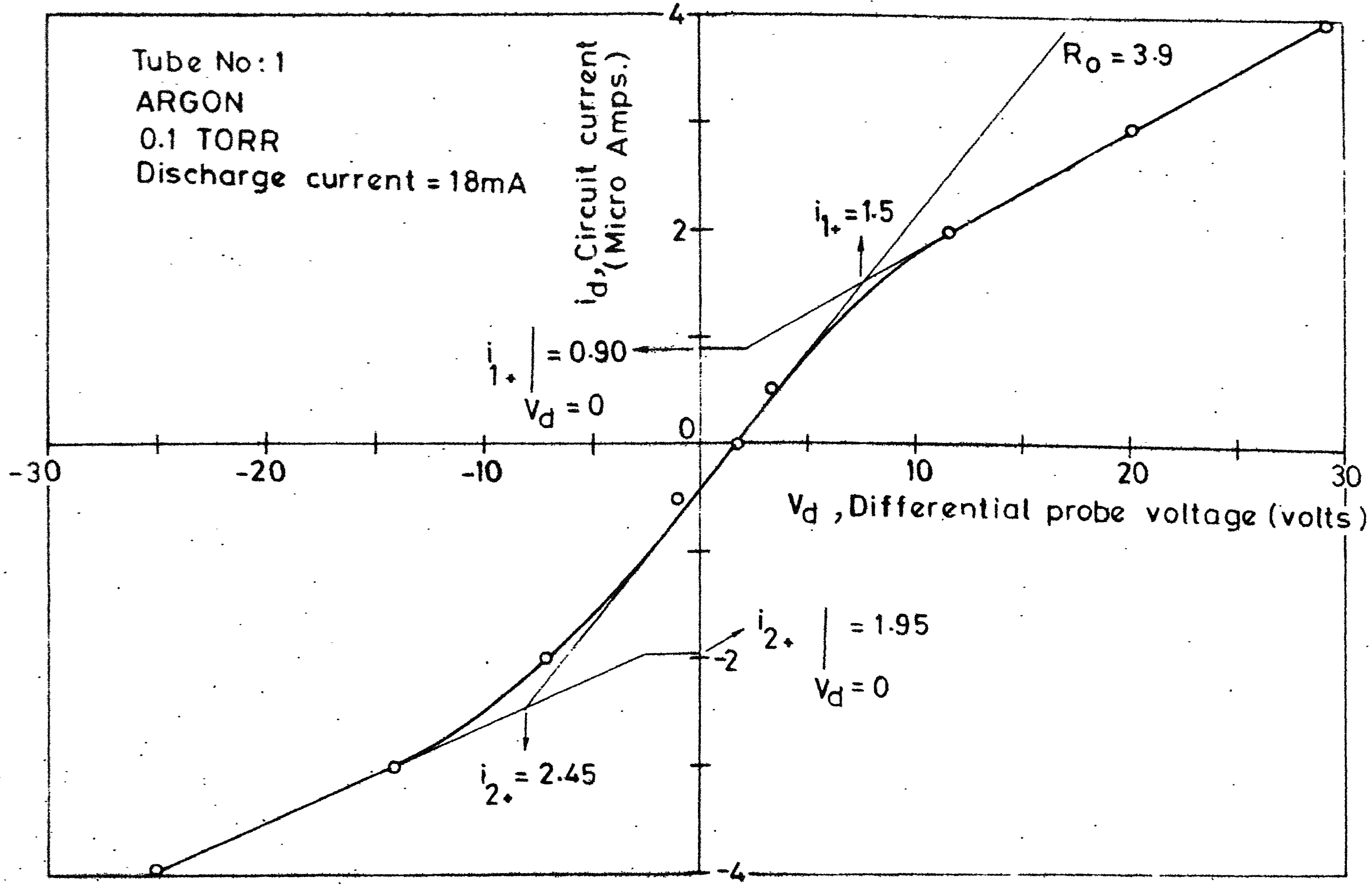


FIG. 17 DOUBLE PROBE CURRENT - VOLTAGE CHARACTERISTIC

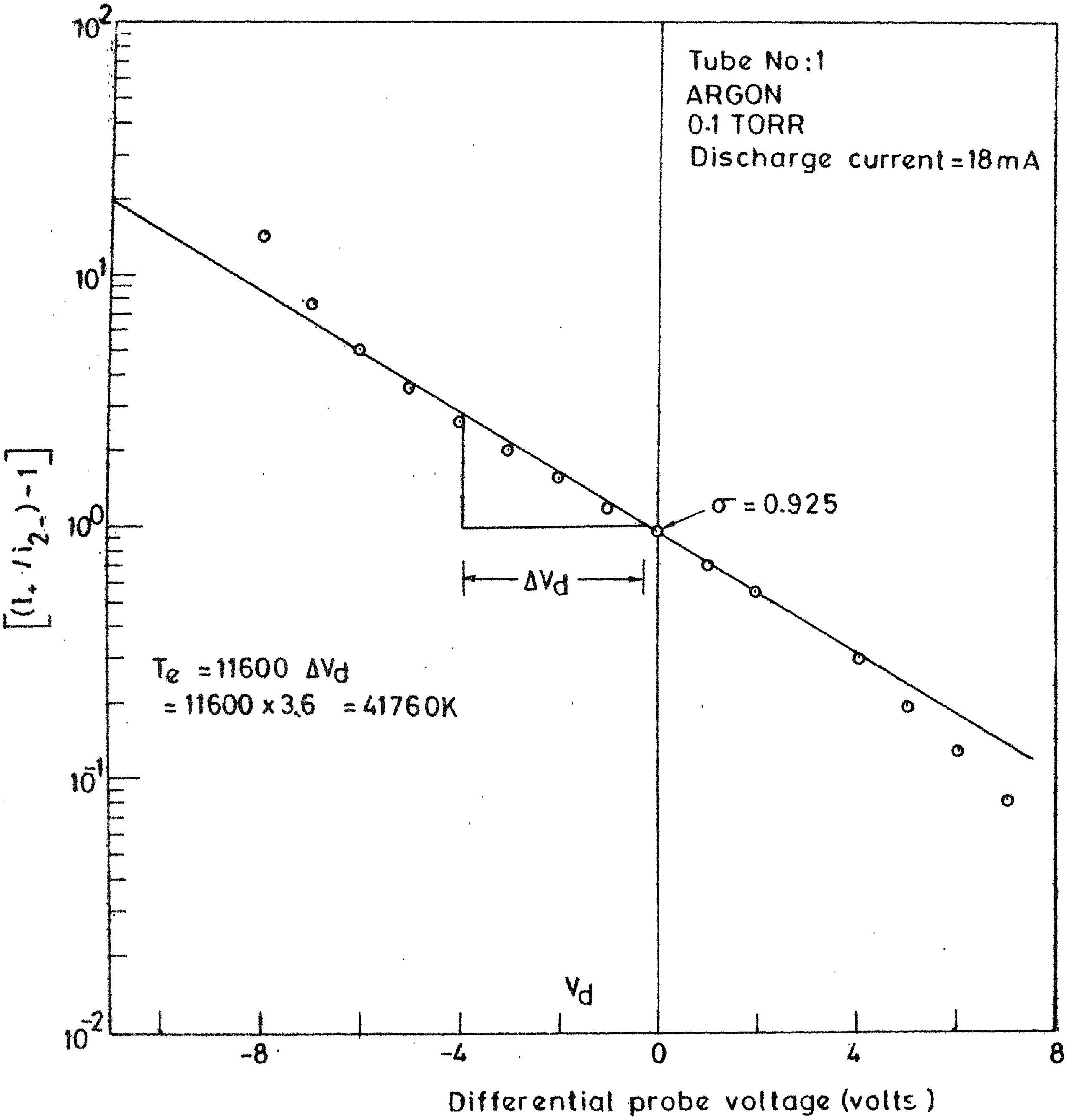


FIG. 18 TEMPERATURE DETERMINATION BY LOG PLOT METHOD

TABLE NO.4

Electron temperature evaluations by different methods

Tube No.1, Argon, 0.1 torr

Discharge current (mA)	Electron Temperature, $T_e \times 10^{-4}$ (K)				
	ERM	LPM	Y-O	ROH	Theoretical
5	1.73	2.13	2.09	1.77	2.18
10	2.82	3.13	3.29	2.96	
15	1.48	1.76	1.74	1.47	
18	3.21	4.18	4.19	3.39	

ERM - Equivalent resistance method

LPH - Logarithmic plot method

Y-O - Yamamoto and Okuda's method

ROH - Rohatgi's method

TABLE NO.5

Values of σ evaluated from ERM and LPM,

Argon, 0.1 Torr, Tube No.1

Discharge current (mA)	σ	
	E R M	L P M
5	1.64	1.65
10	1.18	1.28
15	1.36	1.50
18	0.9	0.93

TABLE NO.6

Electron temperatures in Tube No.1 at different pressures of argon and at different discharge currents

Pressure (torr)	Electron Temperature, $T_e x10^{-4}$				
	Discharge current (mA)				Theoretical
	5	10	15	18	
0.08		3.69			2.31
0.1	1.73	2.82	1.48	3.21	2.18
0.2	2.49	2.08	2.27	2.11	1.85
0.3	4.42	2.71	2.68	2.05	1.70

TABLE NO. 7

Electron temperatures in Tube No.1 at different pressures of nitrogen and at different discharge currents

Pressure (torr)	Electron Temperature, $T_e x10^{-4}$ (K)				
	Discharge current (mA)				Theoretical
	5	10	15	20	
0.05	2.33	2.87	3.5		2.63
0.08	2.36	2.66	2.6	3.28	2.29
0.1	1.68	1.73	2.78	3.58	2.16
0.3	2.62	1.10	1.13	0.82	1.69
0.5	2.73	1.86	1.54	1.40	1.54

TABLE NO.8

Electron temperatures in Tube No.1 at different pressures of Hydrogen and at different discharge currents

Pressure (torr)	Electron Temperature, $T_e x10^{-4}$ (K)				
	Discharge current (mA)				Theoretical
	0.5	1	2	3	
0.05	2.66	2.0	-	2.91	4.70
0.08	1.72	3.52	-	2.71	3.67
0.1	5.54	3.96	2.62	2.94	3.33
0.2	3.69	3.29	3.04	-	2.60
0.3	-	3.58	3.88	3.57	2.31
0.5	2.62	2.02	4.1	-	2.03

TABLE NO.9

Electron temperatures in Tube No.1 at different pressures of Air and at different discharge currents.

Pressure (torr)	Electron Temperature, $T_e x10^{-4}$ (K)			
	Discharge current (mA)			
	5	10	15	20
0.05	3.24	2.43	2.32	
0.08	1.95	3.75	2.73	
0.1	4.06	3.93	3.13	3.63
0.3	1.69	3.06	3.12	1.99
0.5	1.51	1.49	1.01	1.75

TABLE NO.10

Floating potential of Nitrogen in Tube No.1 at different discharge currents and pressures

Pressure (torr)	Floating potential, V_f (Volts) Discharge currents (mA)			
	5	10	15	20
0.05	14.6	18.2	22.5	
0.08	14.8	16.8	16.4	21.0
0.10	10.25	10.6	17.6	23.0
0.3	16.5	6.5	6.73	4.8
0.5	17.5	11.5	9.33	8.5

TABLE NO.11

Electron densities in Tube No.1 at different pressures of argon and at different discharge currents.

Pressure (torr)	Electron number density, $n_{-}x10^{-9}$ (cm^{-3}) Discharge current (mA)							
	5		10		15		18	
	Exptl	Theoretical	Exptl	Theoretical	Exptl	Theoretical	Exptl	Theoretica
0.08			0.47	19.9				
0.1	0.49	13.3	0.43	19.9	3.27	47.9	2.7	32
0.2	1.0	11.1	2.11	23.3	2.36	33.2	2.39	41.6
0.3	0.46	7.97	2.52	21	3.19	31.5	6.95	42.2

TABLE NO 12

Electron densities in Tube No.1 at different pressures of Nitrogen and at different discharge currents.

Pressure (torr)	Electron number density, $n_e x10^{-9}$ (cm^{-3}) Discharge current (mA)			
	5	10	15	20
0.05	1.62	2.06	4.1	
0.08	0.45	2.85	4.31	6.89
0.1	1.58	3.2	4.46	5.15
0.3	0.17	0.39	0.79	1.46
0.5	0.09	0.52	0.28	0.30

TABLE NO.13

Electron densities in Tube No.1 at different pressures of hydrogen and at different discharge currents.

Pressure (torr)	Electron number density, $n_e x10^{-8}$ (cm^{-3}) Discharge current (mA)			
	0.5	1	2	3
0.05	1.36	4.22		4.58
0.08	0.94	1.89		5.59
0.1	0.54	2.80	3.40	5.03
0.2	2.86	4.57	8.45	-
0.3	-	3.13	8.63	1.13
0.5	1.38	5.59	5.25	-

TABLE NO.14

Electron temperatures and number densities in 0.1 torr of argon at different magnetic field strengths when **E is** anti-parallel to H and the discharge current is 5mA

H (Gauss)	$T_e x10^{-4}$ (K)	$n_- x10^{-9}$ (cm^{-3})
0	7.62	6.21
200	5.32	2.88
400	3.71	0.94
600	3.80	1.31
800	3.93	0.66
1000	4.65	1.51

TABLE NO 15

Electron temperatures and densities in 0.1 torr of argon at different magnetic field strengths when E is parallel to H and the discharge current is 5mA

H (Gauss)	$T_e x10^{-4}$ (K)	$n_- x10^{-9}$ (cm^{-3})
0	2.43	9.12
200	2.98	6.00
400	3.94	3.58
600	4.12	2.14
800	5.89	2.75
1000	3.69	1.65

TABLE NO.16

Electron temperatures and number densities in argon at different magnetic field strengths when E is perpendicular to H and the discharge current is 5mA

(a) p=0.1 torr

H (Gauss)	$T_e \times 10^{-4}$ (K)	$n_- \times 10^{-9}$ (cm^3)
0	6.63	13.9
100	3.99	10
150	6.12	6.22
200	5.98	2.57

(b) p =0.2 torr

H (Gauss)	$T_e \times 10^{-4}$ (K)	$n_- \times 10^{-9}$ (cm^3)
100	8.22	2.51
150	8.50	1.81
200	7.06	2.42
250	11.1	1.36
300	11.6	0.95

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A P P E N D I X E S

APPENDIX-A

Values of the constant C and ionization potential V_i for various gases.

Gas	C $(\text{mm Hg.cm})^{-1}$	V_i (Volts)
He	4×10^{-3}	24.58
Ne	6×10^{-3}	21.6
Ar	4×10^{-2}	15.755
Hg	7×10^{-2}	10.434
H_2	1×10^{-2}	15.422
N_2	4×10^{-2}	15.576

APPENDIX B

β^2 as a function of r_s/r_p

$\frac{r_s}{r_p}$	β^2	$\frac{r_s}{r_p}$	β^2
1.00	0.00000	6.0	14.343
1.01	.00010	6.5	16.777
1.02	.00040	7.0	19.337
1.04	.00159	7.5	22.015
1.06	.00356	8.0	24.805
1.08	.00630	8.5	27.701
1.10	.00980	9.0	30.698
1.15	.02186	9.5	33.791
1.2	.03849	10.0	36.976
1.3	.08504	12.0	50.559
1.4	.14856	14.0	65.352
1.5	.2282	16.0	81.203
1.6	.3233	18.0	97.997
1.7	.4332	20.0	115.64
1.8	.5572	30.0	214.42
1.9	.6947	40.0	327.01
2.0	.8454	50.0	450.23
2.1	1.0086	60.0	582.14
2.2	1.1840	70.0	721.43
2.3	1.3712	80.0	867.11
2.4	1.5697	90.0	1018.5
2.5	1.7792	100.0	1174.9
2.6	1.9995	120.0	1501.4
2.7	2.2301	140.0	1843.5
2.8	2.4708	160.0	2199.4
2.9	2.7214	180.0	2567.3
3.0	2.9814	200.0	2946.1
3.2	3.5293	250.0	3934.4
3.4	4.1126	300.0	4973.0
3.6	4.7298	350.0	6054.1
3.8	5.3795	400.0	7172.1
4.0	6.0601	500.0	9502.2
4.2	6.7705		
4.4	7.5096		
4.6	8.2763		
4.8	9.0696		
5.0	9.8887		
5.2	10.733		
5.4	11.601		
5.6	12.493		
5.8	13.407		

APPENDIX C

```
      C     PROGRAM TO CALCULATE THE ELECTRON TEMPERATURE IN
      C     POSITIVE COLUMN OF THE GLOW DISCHARGE IN ARGON AT
      C     VARIOUS PRESSURES(0.05 TORR TO 0.5 TORR).
      C     THE GOVERNING EQUATION IS X=11.906+2LN(P)+0.5LN(
      C     DISCHARGE TUBE DIMENSIONS:LENGTH=16cm,RADIUS=2.8
      C                                :LENGTH=8.5CM,RADIUS=2.
      C     FOR ARGON IONIZATION POTENTIAL=15.7V,C=0.04
      C     THIS EQUATION IS SOLVED FOR X USING SUCCESSIVE A
            DIMENSION X(100),Y(100)
            TYPE 120
      120   FORMAT(15X,'ELECTRON TEMPERATURE OF ARGON IN  TU
            TYPE 70
      70    FORMAT(6X,55(1H_))
            TYPE 80
      80    FORMAT(5X,'|',2X,'PRESSURE   |', 2X,'  PR       |
            1 TEMPERATURE',3X,'|')
            TYPE 90
      90    FORMAT(5X,'|',2X,'IN mmHg     |',11X,'|     EV
            1KELVINS',1X,'|')
            TYPE 100
      100   FORMAT(5X,'|',55(1H_),'|')
            P=0.05
            J=0
      5     X1=0.6
            R=2.572
            Z=P*R
            EPSILN=1.0E-06
      10    Y1=11.906+2*ALOG(P)+0.5*ALOG(X1)
            IF(ABS(X1-Y1).LE.EPSILN)GOTO 20
            X1=Y1
            GOTO 10
```

```
20     EVTEMP=15.7/Y1
       DGTEMP=EVTEMP*11500
       TYPE 30,P,Z,EVTEMP,DGTEMP
30     FORMAT(5X,'|',3X,F5.2,5X,'|',2X,F7.3,2X,'|',2X,F7
       1.2,7X,'|')
       X(J)=Z
       Y(J)=DGTEMP
       WRITE(23,1) X(J),Y(J)
1      FORMAT(1X,F7.3,5X,F8.2)
       J=J+1
       IF(P.LT.0.1)GOTO 40
       IF(P.LT.0.5)GOTO 50
       IF(P.EQ.0.5) GOTO 60
200    P=P+0.5
       GOTO 5
40     P=P+0.01
       GOTO 5
50     P=P+0.1
       GOTO 5
60     TYPE 110
110    FORMAT(6X,55(1H-)//)
       WRITE(23,2) J
2      FORMAT(1X,'NUMBER OF POINTS TO BE PLOTTED=',I4)
       STOP
       END
```

NE-1984-M-GOP-DET